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A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 18th, 1902.

A METHOD OF COMPOUNDING ALTERNATING CURRENT GENERATORS AND MOTORS, DIRECT CURRENT GENERATORS, SYNCHRONOUS MOTOR-GENERATORS AND SYNCHRONOUS CONVERTERS.

BY FRANK GEORGE BAUM.

The weakest element in the regulation of an alternating current system is usually the generator. Makers of engine and water wheel governors are able to keep the variations in speed in the machines which they send out much lower than builders of A. C. generators are able to keep the variations in voltage. The time is past when the man who is selling a generator points with pride to the fact that the machine may be short-circuited with little increase over nominal current. The argument that compounding of alternating current generators is not necessary because load changes are not rapid, does not hold, as the fluctuation of voltage of 10% or more in some stations testifies. Working an alternating current station without compounding is equivalent to operating a direct current station with shunt-wound separately excited generators. When induction motors are to be operated, as is usually the case, the conditions are worse. No electrical engineer would install shunt-wound direct current generators, even if the load changes were not rapid, and the only reason for not installing compounded alternators is that there is at present no method by which the compounding may be produced for large stations. There are methods of compounding single machines which are more or less successful, but no method, I believe, for large stations, which gives results that can be compared with those obtained by compounding D. C. generators.

The following method of compounding alternating current generators for any load and any power factor, so that we may get results equal to those obtained by compounding D. C. generators will, I believe, commend itself to electrical engineers. In some respects, the method is simpler than in the case of D. C. generators, as will be shown.

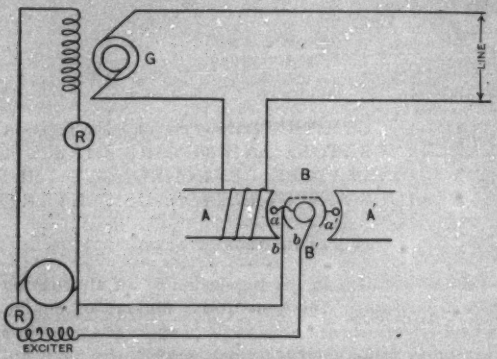

FIG. 1.—Showing Possible Connections of Compensator.

Fig. 1 shows the connections of the " compensator," as it may be called. G is the generator, which, for the purpose of explana-

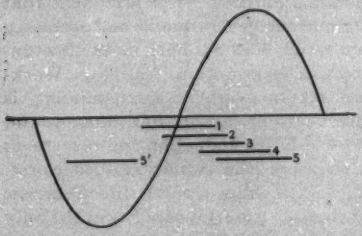

FIG. 2.—Showing Method of Obtaining a Rectified Potential.

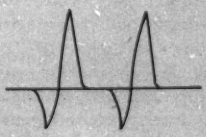

FIG. 3.—Trace of Oscillograph Record for Second Position in Fig. 2.

tion, may be considered a two-pole machine. From its shaft is driven the armature $a\,a'$, having field poles A A'. The armature winding may be considered a single turn of wire, as shown. One end of the armature wire goes to a solid ring and the other end to a ring broken as shown, but the two parts are metallically

connected. It is to be noticed particularly that there is no commutation, the same armature wire being always connected to the same brush. Brushes are placed on these rings as shown, the brush on the broken ring being in the center of one pole. The metallic segments of the broken ring cover about 90 electrical degrees.

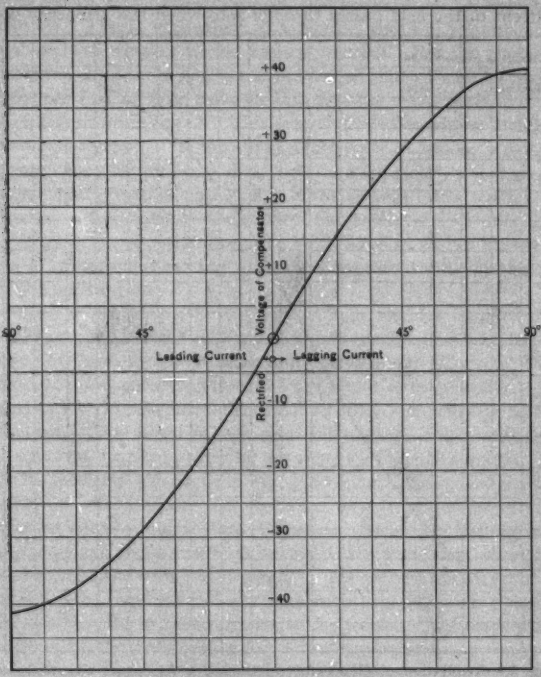

FIG. 4.—Curve of Rectified Voltage of Compensator, with Constant Field Current and Variable Angle.

If the field A A′ were excited by a direct current we would get at the brushes, parts of an alternating wave, a part of each wave being cut out owing to the fact that the ring is divided. If we excite A A′ by a sinusoidal alternating current in synchronism with the rotation of the armature $a\,a'$, we get waves of e.m.f. at the brushes of different forms, depending on the position of the

armature coil when the current passes through its maximum value. For example, if the armature coil passes the position shown when the current in the field coil is a maximum, it will be evident that we get a rectified potential at the brushes *b b*. We really cut off the top of the wave and thus get a potential at *b b* which may be measured by an ordinary D. C. voltmeter. If the current in the field passes through zero when the armature coil

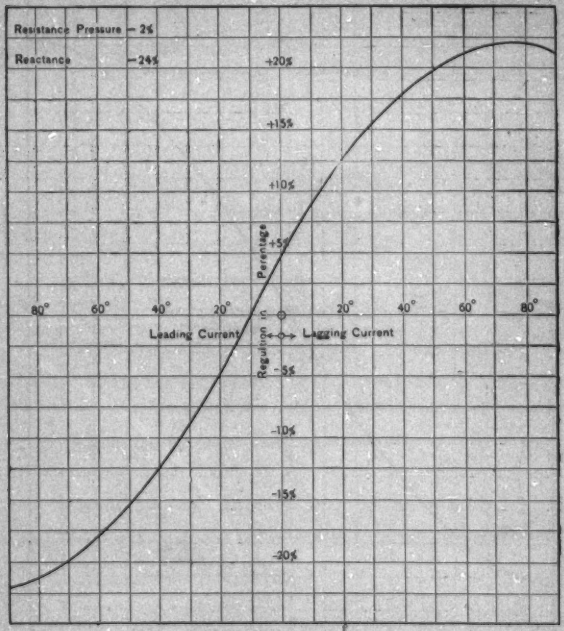

FIG. 5.—Regulation of Generator on Constant Armature Current and Variable Power Factor.

passes the position shown, then we get no rectified potential.

What really occurs for the different positions may be explained with reference to Fig. 2. The sine wave is the wave of current from the alternator, and may also represent the wave of magnetism in the compensator poles A A′. The lines 1, 2, etc., represent the metallic segment for different positions of the armature coil with respect to the wave of magnetism. If the current

is passing through zero when the coil is in the position shown in Fig. 1, then we cut off the part of the wave under the line 1, and hence get an alternating potential. There will also be an alternating e.m.f. due to the transformer action, but no account need be taken of this. Now, suppose the current lags behind this position. This is equivalent to a motion ahead of the metallic segment with respect to the wave of current. For the position 2 of the metallic segment, we would cut off that part of the wave under the line 2. Fig. 3 shows a trace of the e.m.f. wave for the second position in Fig. 2. This record was taken with a Blondel band oscillograph. As the current lags more and more, we pass through the positions 1, 2, 3, 4, to 5, for a lag of 90°, which gives us maximum rectified potential. If the current leads, there is a relative motion between the wave of magnetism and the metallic segment in the opposite direction. For 90° lead we get the position 5′, giving us a reading equal and opposite to that obtained for the position 5.

Fig. 4 shows a curve between the voltage read by a D. C voltmeter across *b b* and the angle of lag of current (the zero angle does not correspond to a non-inductive current from the generator, but corresponds to the position 1 of the metallic segment in Fig. 2), the current in the field of the compensator being constant. The form of the rectified voltage curve may be changed very easily by varying the arc of the metallic segment. It will be seen that the curve in Fig. 4 is very similar to that shown in Fig. 5, which shows the regulation of a generator delivering constant current, but at different power factors. (By the regulation is meant the percentage by which the generated pressure must exceed the terminal pressure.) We get this same kind of a curve for the regulation of a transmission line. If it were possible, now, to add to the excitation of the generator, amounts proportional to the ordinates in Fig. 5, we would obtain a generator which would regulate on any load and any power factor from 90° lead to 90° lag. The field poles A A′ may be rotated with respect to the armature so that when the alternator is working on a constant load, the different voltages across *b b*, shown by the curve in Fig. 4, may be obtained. Now, we set the poles A A′ with respect to the poles of the alternator, when the alternator is working on a non-inductive load, to correspond about to position 2 for the metallic segment in Fig. 2. That is, we work approximately, as many degrees to the right of the zero point in Fig. 4 as the current lags through the generator. This point may be

easily found with a D. C. voltmeter across $b\,b$, as we merely rotate the field until a certain fraction of the maximum voltage is obtained. This setting takes but a moment and may be made

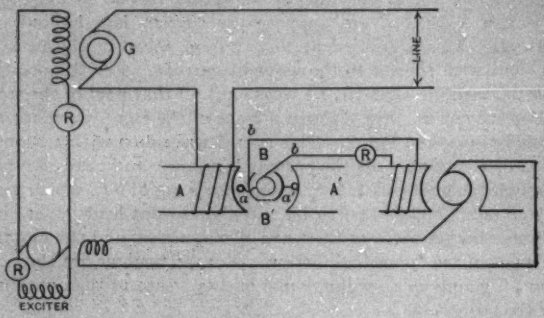

FIG. 6.—Showing Connections of Compensator Used in Practice.

while the alternator and compensator are running

The rectified voltage may now be added to the alternator in several ways. If, then, the current delivered lags behind the

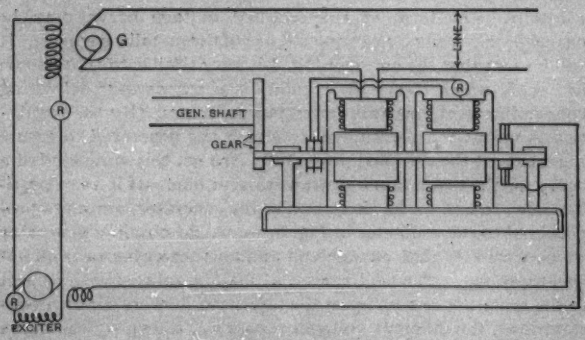

FIG. 7.—Compounding Generator or Synchronous Motor, Showing General Arrangement of Compensator.

terminal pressure of the generator, the potential added will increase according to the curve in Fig. 4. If the current leads, the voltage added will decrease, pass through zero, and then increase in the negative direction.

The rectified potential may be added in series with the exciter field, as shown in Fig. 1. This method gives very good results. It is found that loads of any character may be added to the machine without disturbing the voltage. The generator may also be over-compounded to maintain constant potential at some point on the line.

There are some objections, however, to this arrangement, because it is not "fool proof." The arrangement shown diagrammatically in Fig. 6 has therefore been adopted. As shown, the rectified potential is used to excite a small D. C. generator of 100 to 500 watts capacity, and the armature of the D. C. machine connected in series with the series winding on the exciter. The D. C. current is large, so that only a few turns are needed on the exciter. These may be easily threaded on by hand, if there is not already a series winding on the exciter, so that no new exciter is needed. The percentage compounding may be changed simply by turning the rheostat handle in the armature circuit of the compensator. The compensator has four poles and is driven in synchronism by a gearing on the generator shaft. Fig. 7 shows the general arrangement of the compensator. The compensator set being small, it is a simple matter to add the compensator to any generator.

This method may be applied to compounding alternators operating in parallel, whether the generators have separate exciters or are all excited from the same exciter. When there is a separate exciter for each machine, the compensator may be applied to each generator, or a single compensator may be put on one generator and the current from the D. C. side carried around each exciter field. The station would then, of course, be compounded only when the compensator is running. The entire station may be compounded by a single compensator set where all generators are excited from the same exciter. In this case, the current for the field of the compensator would be taken from the bus-bars.

Since we must supply only a fraction of the exciting energy of the exciter, the compensator set of 500 watts capacity is large enough to compound a 10,000 k.w. station.

Another method of obtaining a rectified potential is that used by Mr. Fitzhugh Townsend[1] in determining the curve of an al-

1—"A New Method of Tracing Alternating Current Curves" by Fitzhugh Towsend, *Transactions*, January, 1900.

ternator. His contact maker consisted of a disk, the perimeter of which in a bipolar alternator, is divided into two sections. One section only is conducting and current flows only for half a period.

This method differs only in detail from that used in commutating the current in the compensator types of alternators now on the market. For numerous reasons this method of compounding is not entirely successful and cannot be used to compound machines running in parallel. The alternating current cannot be successfully applied directly to the field of the alternator to produce the compounding. If however, we apply the rectified voltage to the field of an auxiliary exciter, the troubles due to commutating the current disappear.

It will be seen that this method of compounding is in some respects simpler than the present method of compounding D. C. machines. The following are some of its advantages:

(1) Generators have a single winding.

(2) No equalizer bus-bars, switches, etc. are necessary.

(3) No adjustment of low resistance shunts is necessary to make machines take their proper share of load.

(4) When the generators are over-compounded, there is no drop in voltage when a fresh machine is added.

(5) Percentage compounding may be changed instantly by turning a rheostat handle.

(6) The cost of compounding a large station will be less than compounding the same number and capacity of D. C. generators.

(7) Owing to the absence of equalizer switches, the operation of the station is simpler.

Compounding Synchronous Motors.

At the present time, there is no method of compounding the excitation of synchronous motors other than those driving D. C. generators. The method given for compounding alternating current generators may be used to compound the excitation of alternating current motors. This removes one serious objection to the use of synchronous motors on transmission lines for other purposes than for operating D. C. machines.

Compounding Direct Current Generators.

The method given for compounding alternating current generators is comparable with the method of compounding D. C. generators shown in Fig. 8. Here we excite all the D. C. generators by one exciter and compound this exciter with the load

current from the generators. This does away with the series winding on each machine, as well as all equalizer connections and switches. We are not bothered with the troublesome problem of adjusting a number of low resistance shunts in such a way that all machines will take their proper share of load. There will be no reversal of magnetism and less "slopping over" due to the reversal of the series current. Except for the addition of the exciter, the operation of the station is very much simplified. To provide against the possibility of an injury to the exciter and the consequent disabling of the entire station, the generator fields should be provided with double-throw switches, so that in case of injury to the exciter the generators could be temporarily operated as shunt-wound machines. Shunts 1, 2, 3, etc., with switches, may be put on the exciter

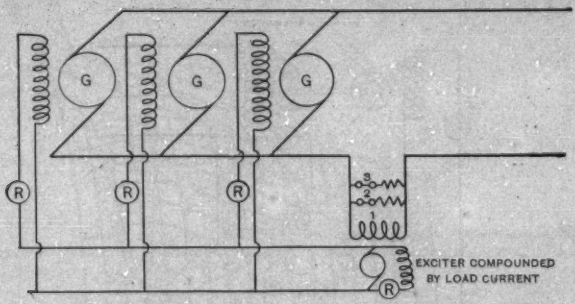

FIG. 8.—Compounding D. C. Generators.

series field, so that the compounding may be made to suit the number of generators running, or to vary the compounding when desired. When the generators are over-compounded, there will not be a drop of line potential when a fresh machine is added, as is the case in the method of compounding each generator. Where there are a number of large generators in a station, this method of compounding seems to be cheaper and simpler in nearly every way, than that commonly used.

COMPOUNDING SYNCHRONOUS MOTOR-GENERATORS AND SYNCHRONOUS CONVERTERS.

The above method of compounding the exciter has been very successfully used to compound the excitation of three motor-generator sets operating on a street railway load at the end of a 150-mile transmission line. The arrangement is shown in Fig. 9

for a single set. All the synchronous motors were, of course, excited from the same exciter. No new exciter was needed, as the motors were already excited by a compound wound exciter. All that was necessary to apply the method was to shunt part of the current from the D. C. side around the exciter series coil. This varied the excitation of the motor so that changes of load had little effect on the line potential at the motor terminals. Before the synchronous motors were compounded, lights could not be operated on account of the excessive variations of potential.

Since a separate exciter is generally used for this kind of work, this method is very much cheaper and simpler than carrying a series winding around the field poles of each motor. This method may also be applied to compounding synchronous converters.

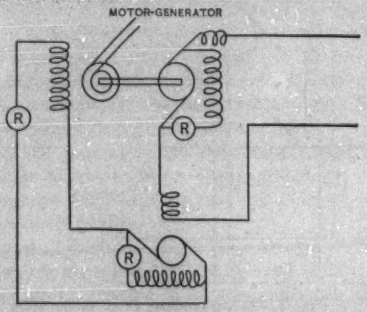

FIG. 9.—Compounding Motor-Generator Exciter Compounded by Load Current.

COMPOUNDING TRANSMISSION SYSTEMS.

In applying these methods of compounding to the most general case of a transmission system with a long trunk line with several branch lines, the generators would be compounded for the center of distribution, and the synchronous motors on each branch line compounded also with respect to the center of distribution.

It is well known that poor regulation is usually the besetting sin of many long-distance transmission systems, and very often the only solution of the problem of getting rid of a large percentage of the power generated is to restrict the motion of the recording voltmeter needles so as to impress possible customers more favorably. Systems are in operation where there is a

variation in voltage of 10 %, and very often when synchronous motors operating on the line get to surging, owing to the bad regulation, there will be a drop or rise of perhaps 20%. This very often makes the cost of lamp renewals as great as the cost of power. Such a system for a mixed load of lights and power must in the end be displaced by something better. On long-distance transmission systems, where the generator capacity is large compared with the load changes which are likely to occur, the pressure at the powerhouse may remain fairly constant and yet vary 10% at the receiver.

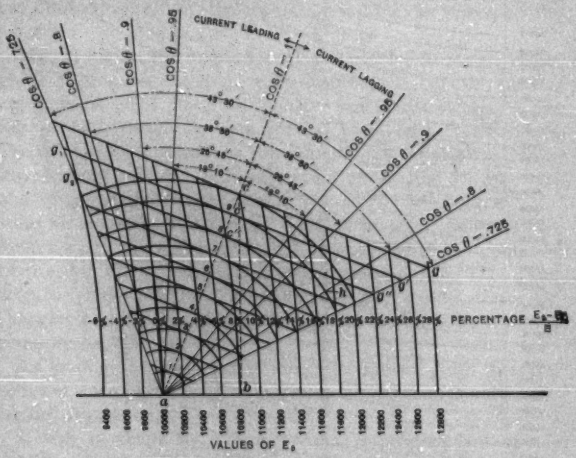

FIG. 10.—Regulation of Transmission System.

Fig. 10 and Fig. 11 bring out in a striking way the effect of changes of load and especially of changes of power factor on the regulation of the line.[1] Fig. 10 represents a 15-mile, 60 p.p.s., three-phase transmission system, with 10,000 volts between neutral and line wire The power transmitted is 3,000 k.w. at full load, with a copper loss of 8%, including step-up and step-down transformers: *o a* is the receiver pressure, the point o not being shown. The pressure consumed over the line by the

1—A Simple Diagram Showing the Regulation of aTransmission System for Any Load and Any Power Factor.By F. G. Baum, *Elec. World and Eng.* May 18, 1901

power component of current is measured along $a\,c$, and the pressure consumed by the wattless current is measured at right

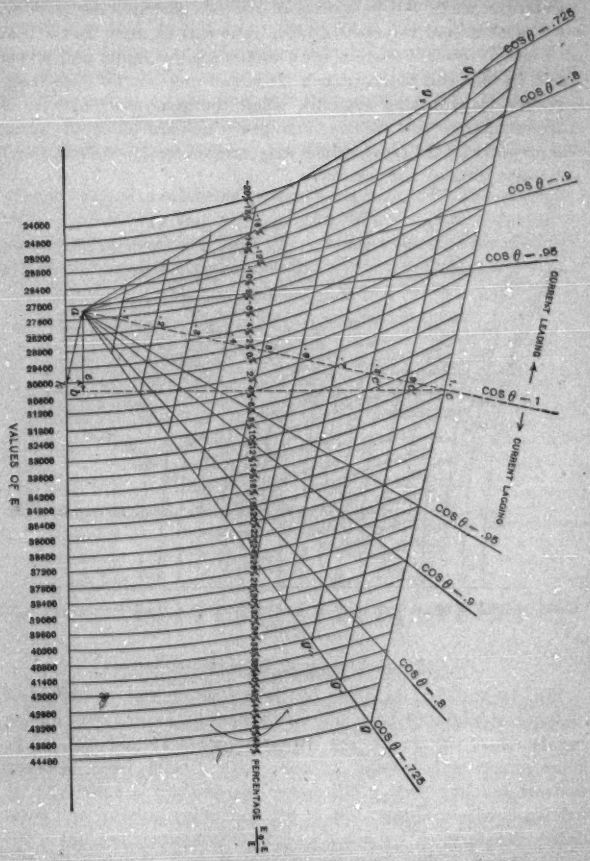

FIG. 11.—Regulation of 150-Mile Transmission Line.

angles to $a\,c$, to the right of $a\,c$ for lagging currents, to the left for leading. $a\,c$, which represents full load, has been divided

into ten equal parts, corresponding to .1, .2, etc., of full load. Through points marked .1, .2, etc., lines have been drawn at right angles to $a\,c$. Radial lines making angles corresponding to $\cos\,\theta = .95$, $\cos\,\theta = .9$, etc., for lagging and leading currents, have been drawn from a. Circular arcs, with the point a as center, have also been drawn through points along $a\,c$ marked .1, .2, etc. The regulation for any load and any power factor may be determined from the figure. For example, find the regulation at .9 full load at .8 power factor: Go along $a\,c$ to $c' = .9$, then along $c'\,g'$ to the intersection with the line $\cos\,\theta = .8$. The regulation is seen to be about $21\frac{1}{2}\%$. For .9 full load current, and the same power factor, the regulation is 17%, as shown by the point h.

Fig. 11 shows the regulation of a 150-mile, 60 p.p.s., three-phase transmission system, with 30,000 volts between neutral and outside. The power transmitted is 9,000 k.w., with a line loss of 10%, including step-up and step-down transformers. The triangle $k\,l\,a$ shows the rise in pressure over the line due to the charging current. The regulation of the line for any load and any power factor is shown.

As an example find $E\,o$ for 0.8 load at 0.725 power factor. Follow $a\,c$ to point c'' (marked .8), then follow $c''\,g''$ to point of intersection of $c''\,g''$ with line marked $cos\,\theta = 0.725$. The point is on the circle 40,800. This is the value of $E\,o$ (36% above E). (Lagging current assumed in example, for leading current $E\,o$ is given by $p\,t.\,g_{,}$).

An intelligent application of the methods here given will, it is believed, even in the worst case, give us a system with very satisfactory regulation.

I wish to thank Mr. Frank Adams, Superintendent of the Stockton Gas and Electric Company, for allowing me the privilege of making the preliminary tests on the compensator in the company's station.

Stanford University, Cal
April, 1902.

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FORMULA FOR CALCULATING THE ELECTROMOTIVE FORCE AT ANY POINT OF A TRANSMISSION LINE FOR ALTERNATING CURRENT.

BY M. LEBLANC.

It is a recognized fact that in long-distance transmission of electrical energy by means of alternating current, the voltage has often been found to be higher at the receiving end than at the generator end of the line. This increase in voltage may be considerable, and it is important to take it into account when making installations.

We intend to establish a formula giving the voltage at any point of an alternating current transmission line. Let us call ρ, γ and λ respectively, the resistance, capacity and self-induction per unit of length of both conductors of a line of length l. Let us send into it an alternating current of frequency $\beta = \frac{m}{2\pi}$ varying as a function of the time according to a sine law. Let us call $\sqrt{V_x}$ the voltage at a point x located at a distance x from the generator end.

The transmission of the current is governed by the equation:

$$\frac{d^2v}{dx^2} = \gamma\lambda\frac{d^2v}{dt^2} + \gamma\rho\frac{dv}{dt}$$

Under constant load, this equation is satisfied if we make, according to Vaschy:

$$V_x = e^{a(l-x)}[A\sin m(t-x/v) + B\cos m(t-x/v)] + e^{-a(l-x)}[D\sin m(t+x/v) + F\cos m(t+x/v)]$$

$$V = \frac{1}{\sqrt{\gamma\lambda}}\sqrt{\frac{2\lambda m}{\lambda m + \sqrt{\rho^2 + m^2\lambda^2}}}; \quad a = \tfrac{1}{2}\gamma\rho v.$$

The velocity v is the speed of transmission of the electric waves along the line.

The intensity i_x at the point x being given by the equation:

$$\rho i_x + \lambda \frac{di_x}{dt} = -\frac{dV_x}{dt}, \text{ we have:}$$

$$(2)\quad \rho i_x + \lambda \frac{di_x}{dt} = e^{\alpha(l-x)}\left[\left(A\alpha - B\frac{m}{v}\right)\sin m\left(t - \frac{x}{v}\right)\right.$$

$$\left. + \left(A\frac{m}{v} + F\alpha\right)\cos m\left(t - \frac{x}{v}\right)\right] + e^{-\alpha(l-x)}\left[\left(-D\alpha + F\frac{m}{v}\right)\sin m\left(t - \frac{x}{v}\right) - \left(D\frac{m}{v} + F\alpha\right)\cos m\left(t + \frac{x}{v}\right)\right]$$

Let us designate by the letter U_x the maximum value of the voltage V_x at the point x; we deduce from equation (1):

$$(3)\quad U_x = \sqrt{e^{2\alpha(l-x)}(A^2 + B^2) + e^{-2\alpha(l-x)}(D^2 + F^2) + 2\sqrt{(A^2 + B^2)(D^2 + F^2)}\cos 2m\left(\frac{x}{v} - u\right)}$$

by taking:

$$\text{Tang } 2mu = \frac{BD - AF}{AB + BD}$$

In order to determine the quantities A, B, D, F, we assume that the maximum value U of the voltage at the far end of the line is given, and that the line is closed on a conductor of resistance r and self-induction L.

Let us make $V_l = U_l \times \sin m\,t$ and $T\,g\,m\,\varphi = \dfrac{m\,L}{r}$

then:

$$\rho i_l + \lambda \frac{d\,i_l}{dt} = \frac{U_l}{\sqrt{r^2 + m^2 L^2}}\left[\rho \sin m\,(t - \varphi) + m\,\lambda \cos m\,(t - \varphi)\right]$$

If we write that the equations (1) and (2) are satisfied at any instant of the time, for $x = 1$, we obtain the four following equations which determine A, B, D and F.

$$U_l = (A + D)\cos\frac{m\,l}{v} + (B - F)\sin\frac{m\,l}{v}$$

$$O = -(A - D)\sin\frac{m\,l}{v} + (B + F)\cos\frac{m\,l}{v}$$

$$\frac{U_l}{\sqrt{r^2 + m^2 L^2}}\,(\rho\cos m\,\varphi + m\,\lambda\sin m\,\varphi) =$$

$$(A\,a - B\frac{m}{v} - D\,a + F\frac{m}{v})\cos\frac{m\,l}{v} + (\frac{A\,m}{v} + B\,a + D\frac{m}{v} + F\,a)\sin\frac{m\,l}{v}$$

$$\frac{U_l}{\sqrt{r^2 + m^2 L^2}}\,(m\,\lambda\cos m\,\varphi - \rho\sin m\,\varphi) =$$

$$(-A\,a + B\frac{m}{v} - D\,a + F\frac{m}{v})\sin\frac{m\,l}{v} + (A\frac{m}{v} + B\,a - D\frac{m}{v} - F\,a)\cos\frac{m\,l}{v}$$

If we make:

$$\frac{U_l}{\sqrt{r^2 + m^2 L^2}} = I_l \text{ Tang } m\,\varphi = \frac{\frac{m}{v}}{a} \text{ Tang } m\,X = \frac{m\,\lambda}{\rho};$$

$$(\varphi - X) = +\delta$$

As we have:

$$a^2 + \frac{m^2}{v^2} = m\,\gamma\sqrt{\rho^2 + m^2\lambda^2}$$

We can write:

$$2\,A = U_l\cos\frac{m\,l}{v} + \sqrt{\frac{\sqrt{\rho^2 + m^2\lambda^2}}{m\,\gamma}}\,I_l\cos m\,(\frac{l}{v} - \varphi + \delta)$$

$$2\,B = U_l\sin\frac{m\,l}{v} + \sqrt{\frac{\sqrt{\rho^2 + m^2\lambda^2}}{m\,\gamma}}\,I_l\sin m\,(\frac{l}{v} - \varphi + \delta)$$

$$2\,D = U_l\cos\frac{m\,l}{v} - \sqrt{\frac{\sqrt{\rho^2 + m^2\lambda^2}}{m\,\gamma}}\,I_l\cos m\,(\frac{l}{v} + \varphi - \delta)$$

$$2\,F = -U_l\sin\frac{m\,l}{v} + \sqrt{\frac{\sqrt{\rho^2 + m^2\lambda^2}}{m\,\gamma}}\,I_l\sin m\,(\frac{l}{v} + \varphi - \delta)$$

Equation (3) will be expressed as follows:

$$U_{x'}^2 = \frac{1}{2}\Bigg\{ U^2_l \left(e^{2a(l-x)} + e^{-2a(l-x)} + 2\cos\frac{2m}{v}(l-x)\right) + \frac{\sqrt{\rho^2+m^2\lambda^2}}{m\gamma} I^2_l \left[e^{2a(l-x)} + e^{-2a(l-x)} - 2\cos\frac{2m}{v}(l-x)\right] + 2\sqrt{\frac{\sqrt{\rho^2+m^2\lambda^2}}{m\gamma}}\, I_l U_l \left[\begin{matrix}\left(e^{2a(l-x)} - e^{-2a(l-x)}\right)\cos m(\varphi+\delta) \\ +2\sin\frac{2m}{v}(l-x)\sin m(\varphi+\delta)\end{matrix}\right]\Bigg\}$$

if we take:

$$\text{Tang } m\delta = \frac{m(\rho - \lambda v a)}{m^2\lambda + \rho v a} = \frac{\rho}{m\lambda + \sqrt{\rho^2+m^2\lambda^2}}$$

Such is the expression for the e.m.f. at the point x, located at a distance x from the generator end, when supplying to the receiving apparatus, with a power factor equal to cos $m\varphi$, a current of intensity I_l, of frequency $\beta = m/2\pi$, with a voltage U^l.

Let us consider the line when operated at no load.

We have $I = O$, then the voltage U_0 becomes

$$U_0 = U_l \sqrt{\frac{e^{2al} + e^{-2al} + 2\cos\frac{2ml}{v}}{4}}$$

For a line to transmit energy efficiently, the coefficient of damping $2\,a\,l$ will be always very small, and the sum $e^{2al} + e^{-2al}$, will be approximately equal to 2.

If the line be rather long and cos $2\,ml/v$ differs little from unity, we have $U_1 > U_0$.

This effect will be maximum when:

$$2\frac{ml}{v} = \pi, \text{ or } l = \frac{1}{4}\frac{v}{\beta}$$

Thus, the length of the line will be equal to $\frac{1}{4}$ of the length of the transmitted wave, and the ratio U_1/U_0 will be very high.

This condition will not generally occur with currents of usual frequency, but it may occur on long lines with low harmonics which will bring dangerous surgings in the voltage of the line.

Therefore, we must avoid with the utmost care the production of harmonics by the generating and receiving apparatus, and use in long distance transmission currents with frequency as low as possible, in order that the length of the line may be always very short as compared with the length of the waves transmitted.

A formula similar to the preceding may be deduced giving the intensity I_x at a given point x of the line located at a distance x from the generator end. Then we have :

$$I_x = \tfrac{1}{2}\sqrt{\frac{m\gamma}{\rho^2+m^2\lambda^2}}\Bigg|\sqrt{\begin{aligned}&U^2_l\left[e^{2a(l-x)}-e^{-2a(l-x)}-2\cos 2m\frac{l-x}{v}\right]\\&+\frac{\sqrt{\rho^2+m^2\lambda^2}}{m\gamma}I^2_l\left[e^{2a(l-x)}+e^{-2a(l-x)}\right.\\&\qquad\left.+2\cos 2m\frac{l-x}{v}\right]\\&+2\sqrt{\frac{\sqrt{\rho^2+m^2\lambda^2}}{m\gamma}}I_l\,U_l\\&\left\{\begin{aligned}&\left(e^{2a(l-x)}-e^{-2a(l-x)}\right)\cos m(\varphi-\delta)\\&-2\sin 2m\frac{l-x}{v}\sin m(\varphi-\delta)\end{aligned}\right\}\end{aligned}}$$

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THE NEW GENERATING PLANTS OF THE NIAGARA FALLS POWER COMPANY.

BY H. W. BUCK.

The growth of the applications of Niagara Falls power has been so rapid since the starting up of the first power-house in 1895 that the entire 50,000 h.p. of the first plant has been taken up to its limit. This growth was anticipated by the company three years ago, when the hydraulic development of a second plant was started under way. This plant is nearly completed and within a few months the first generator of its equipment will be performing useful work.

This power-house, from a popular standpoint, may be considered a duplicate of the old one, with which every engineer is familiar, and differs only in some of its technical details. It is located on the opposite side of the intake canal and nearer to the river, and has its water wheels placed at the bottom of its own separate wheel pit. Discharge water is led out from this pit by a branch tunnel, which after leading independently for about 600 feet, joins the main tunnel, which, as is known, has a capacity of 100,000 h.p. The new turbines are somewhat different from those in power-house No. 1, being of the internal discharge type and having the discharge water carried off through draught tubes, which add about 10% to the effective head. This increase in efficiency gives 10% more power for the same amount of water used in power-house No. 1, and in consequence the plant is laid out for 11 units of 5,000 h.p. each, instead of 10. The turbines were designed by Escher, Wyss & Co., or Zurich, and were built by the I. P. Morris Company, of Philadelphia. The

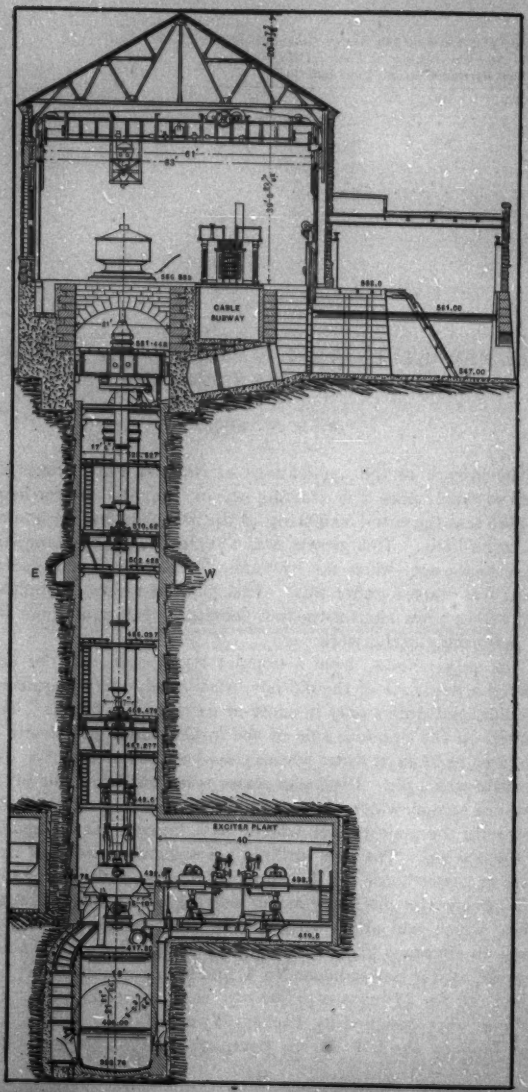

FIG. 1.—Section of Power-House No. 2.

governors were also designed by Escher, Wyss & Co., and are being built by A. Falkenau of Philadelphia. They are of the oil pump operated type and give a maximum variation of speed of about 5%, with 100% load variation, and for fractional changes in load the regulation obtained is about the same as that of a good steam engine.

The electrical equipment is furnished throughout by the General Electric Company. In general, its characteristics are the same as in the apparatus in power-house No. 1. The generators are of 5,000 h.p. each (3,750 k.w.) wound for 2,300 volts, two-phase, 25 cycles at 250 r.p.m. This type was decided upon on account of its exact interchangeability with power-house No. 1. It was considered that the advantages which might result from winding the new generators for a higher voltage, would be more than offset by the lack of interchangeability between two power-houses located so near together as to be governed by the same conditions.

Electro-technically, power-house No. 2 differs in several essential details from the installation in the old plant, the differences being due largely to the advance of the art since the time when the first power-house was equipped. The main points of difference are:

(1) Closer generator regulation, the regulation on the new machines being 10% and on the old ones about 30%.

(2) The entire plant will be operated from a single switchboard instead of two.

(3) The feeders will be protected with automatic oil circuit-breakers.

Generators.

The first six generators to be installed will be similar in outline to those in the first plant, being of the external field type, with the nickel-steel revolving magnet ring. This machine is shown in assembly in Fig. 2. In appearance the most striking difference is in the omission of the iron bridges over the machines. This omission results from the collector rings being placed at the bottom of the dynamo shaft, instead of at the top.

As stated above, the principal difference in these new generators is in the matter of regulation, the regulation being nearly three times as close. This closer regulation was adopted in order to insure constancy of voltage on the system with variations in load, and also to reduce to a minimum the unbalancing

of the voltages on the different phases caused by difference in loads upon them. These points are of great importance on such a system as that of the Niagara Falls Power Company. Many electrical distribution systems are made up of a very large number of small consumers of power and the actions of any one customer have little effect upon the voltage of the system; consequently, in such cases, regulation is not of such vital importance. But the Niagara Falls system is made up of a comparatively small number of very large consumers of power, any one of whom may, by a change in his load, cause a serious disturbance on the circuits. Furthermore, it is unique in one of its characteristics, in that much of the power is used on large single-phase electric furnaces, which take their power from one phase only. Since it is impossible to control these furnaces, so that at all times the same number shall be in operation from each of the two phases, inequality of load on the phases results and the voltages are unbalanced. This unbalancing is disastrous to polyphase synchronous and induction motors on the system, for the high voltage phase tends to carry all the load, and the windings on this phase are overloaded. These results can be rendered inappreciable only by the use of generators of close regulation.

The armature winding is a two-circuit series closed winding and consists of formed one-turn coils placed in open slots with two coils to a slot. The conductor is made up of stranded cable pressed into rectangular shapes. This stranding of the conductor reduces eddy current losses in the armature conductor itself which exist in the case of a large solid bar, as used in the old machines. The open slot is also considered an advantage in a machine of such great length of armature core, for in the closed slot it is necessary to drive the armature bar with its insulation on throughout the length of the slot in order to put it in place. The system of interlacing the end windings used in the new machines gives strong construction to withstand the displacement strains caused by short circuits.

The system of ventilation is radically different in the new machines. Referring to Fig. 2, a baffle plate will be seen between the bottom of the armature winding and the bottom of the revolving field. This forces all the air which is actuated by centrifugal pressure to enter the machine at the bottom inside of the armature shell. From here the air passes outward through the air ducts in the armature core, cooling the iron and the winding. It then continues outward radially between the layers of

the field winding into an annular space at the back of the field coils and thence outward through holes in the magnet ring, which are bored in line with the pole-piece bolts. The action is that of a centrifugal blower, caused by the rotation of the field poles and ring. Some of the air also passes outward at the top of the ring through ventilating holes provided for the purpose. The operation of the air system is very satisfactory, and the blast of air secured is tremendous. From tests which have

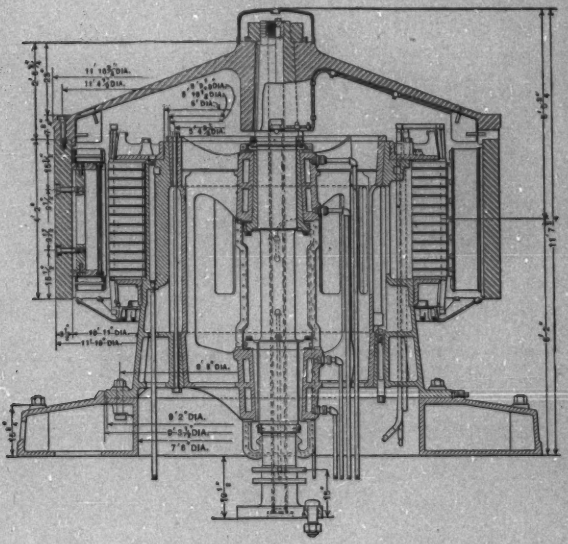

FIG. 2.—External Field 5000 H. P. Generator, Power-House No. 2.

thus far been made, it is believed that these machines will run from 10° to 15° cooler than the old ones. These improvements in design were introduced by Mr. W. L. R. Emmet of the General Electric Company, with the coöperation of Mr. H. G. Reist.

The generator equipment in this power-house is completed with five 5,000 h.p. machines of the internal revolving field type shown in Fig. 3. It was decided that the last five machines of the installation should be of this type on account of the much

lower cost of building, simplicity of handling and accessibility to the various parts, as compared with the external field design. These machines are also wound for 2,300 volts, 25 cycles, two-phase and operate at a speed of 250 r.p.m.

These machines will have the same regulation as the first six installed, and in other respects the electrical constants will be the same. From the drawing in Fig. 3, the construction may be clearly seen. It is similar to the standard horizontal shaft engine-driven alternators of well-known types, and its

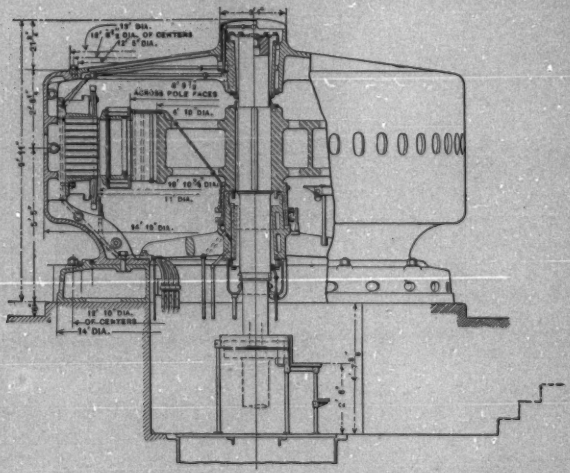

FIG. 3—Internal Field 5000 H P. Generator, Power-House No. 2.

method of ventilation is the same. Recent improvements in the mechanical construction of generators have made this type possible at the high speed of 250 r.p.m. and improvements in water-wheel governors have made permissible the lower fly wheel effect incident to this design, and the consequent omission of the nickel-steel ring of the first machines.

In the two power-houses, then, there will be three types of generator, but no trouble is expected in operating all the machines in parallel. As is well-known, when two alternators of different regulation operate in parallel, the resultant regulation is the mean

between the two. Idle current between the two types may be prevented by careful adjustment of the field currents.

The guaranteed efficiency of the external field generators was;

Full load.....98%
¾ load.....97.3%
½ load.....96%

From actual test, the full load efficiency has come out 98.15%, which is probably the highest ever attained in an electrical generator.

Exciter Plant.

The exciter plant in the new power-house will be quite different in arrangement from the old one. The installation will be made complete with the exciter switchboard in a compartment recessed into the rock at the bottom of the main wheel-pit, as shown in Fig. 1. This position will eliminate the long shaft necessary with exciters placed on the main dynamo floor and will simplify the operation of the plant. The equipment will consist of four 150 k.w.compound wound, vertical shaft, 220 volt exciters each coupled to an independent turbine, placed directly underneath. The speed is 750 r.p.m., and each exciter turbine is controlled by a separate governor. The exciter plant wiring diagram is shown in Fig. 8. It will be seen that the power-house lights and auxiliary motors will be operated from this plant. A panel is also provided for interconnection with the exciter plant in power-house No. 1. The double set of bus-bars permits of the separation of exciting circuits and lights and motors. The exciter compartment will be directly connected by telephone with the main generator switchboard.

Main Switchboard.

As in all plants, the most important element for successful operation is the layout of the switchboard apparatus. The switchboard in power-house No. 2 has been carefully considered and is believed to be convenient and as simple as it can be made and still accomplish the desired results. There has been a tendency in the design of some of the recent large switchboards, toward complexity and the installation of unessential appliances which by their presence cause more trouble and confusion *per se* than that which they are intended to prevent. This has been avoided as far as possible in the design of this board.

Fig. 4 shows a plan of the power-house floor and the relative positions of generators, switchboard gallery, oil switches and

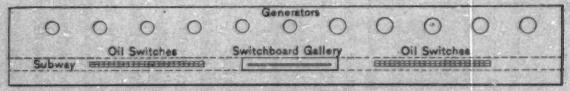

FIG. 4.—Floor Plan of Power-House No. 2.

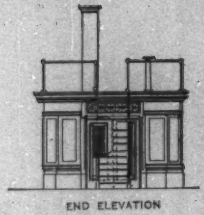

FIG. 5a.

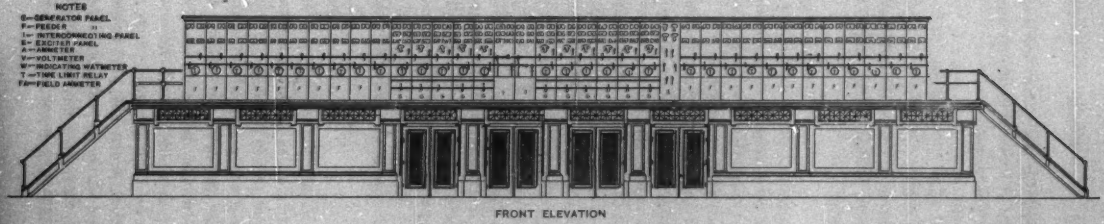

FIG. 5.—Main Switchboard of Power-House No. 2.

cable subway. Fig. 6 shows a section through the oil switches and cable subway and indicates the location of the bus-bars placed in fireproof compartments. Fig. 5 shows a front elevation of the main switchboard gallery and controlling panels. In respect to switching the power-house is divided into two parts, one of six generators and one of five. Each part has its own group of oil switches and its double set of bus-bars. Fig. 10 shows the relations between the two groups and also the inter-

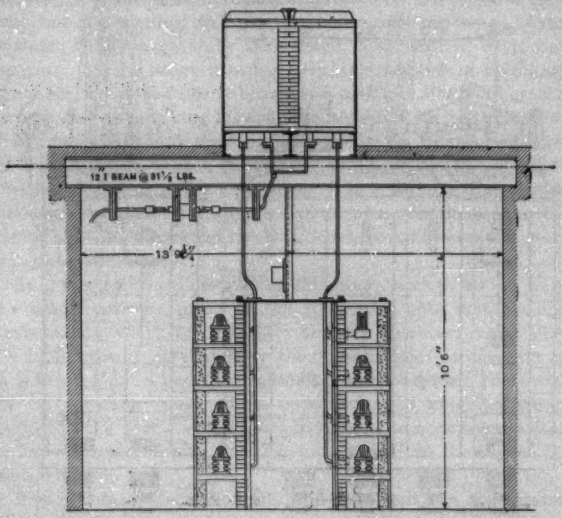

FIG. 6.—Section through Cable Subway under Oil Switches showing Bus-Bars, etc.

connections with power-house No. 1. All the switches in the new power-house are the General Electric electrically operated oil break type of the well-known design. This switch is shown in Fig. 7. All cables are led through the cable subway. They are heavily insulated with rubber, covered with a fireproof braid and supported on brackets with porcelain clamp insulators.

The main switchboard consists of a gallery in the center of the building, having mounted on it 36 separate controlling panels:

11 generator, 22 feeder, 2 interconnecting and 1 exciter panel. The relative location of these panels may be seen in Fig. 5, together with their equipment. All the switching is done on these panels by means of relay switches, placed in distinctive relation to one another and in such a relation to imitation bus-bars placed throughout the face of the switchboard, that the connections are clearly indicated and no mistake in switching can easily

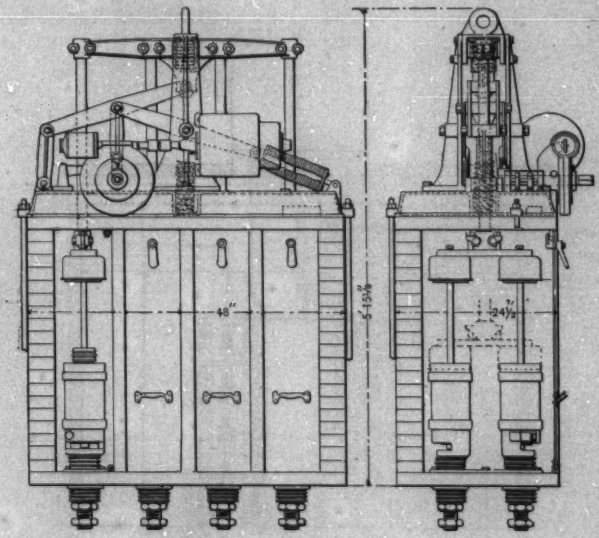

FIG. 7.—2200 volt, 2-Phase Electrically operated Circuit-Breaker, Power-House No. 2.

be made. On the generator panels are two selector relay switches and one generator relay switch; on the feeder panels are two relay selector switches, and on the interconnecting panels are relay interconnecting switches, for making the various connections between the two groups in the new power-house and between the two power-houses. On the sub-bases of the generator panels are dummy exciter bus-bars, with relay double-throw generator field switches. All these relay switches operate

electrically the real switches on the power-house floor and have the exact relation to the dummy bus-bars which the real switches have to the real bus-bars, so that even a green man could hardly make a mistake in throwing a switch. Return indicators are placed adjacent to the relay switches, so that the operator may tell at once whether the real switch has responded correctly to the movement of the relay.

There has been a considerable craze during the last few years for the operation of switchboard apparatus by bench-board control, but in designing the board for this plant, the bench-board system, although carefully considered, was rejected as inconvenient. In the bench-board system, the operator in switching must first go to the bench-board and pick out the relay switch in question, then taking his eye off the switch, he must pick out from a concentrated mass of instruments in front of him on entirely separate panels, the instruments involved in the movement which he is about to make. This is not altogether convenient, and there is always a chance of a mistake. It is believed that the advantages of this bench-board system are more imaginary than real.

In the switchboard installed in this plant, each panel is a complete unit, and comprises all the apparatus, both switches and instruments, which are necessary for any operation which may be made upon it, so that when the operator goes to a feeder or a generator panel he has before him, enclosed within the limits of the particular panel, all the apparatus with which he is concerned at the time. All synchronizing will be done by means of a Lincoln synchronizer placed upon a swivel on the top of the switchboard.

The generator field rheostats and field switches are located under the main switchboard gallery. All feeders are equipped with recording wattmeters installed in the basement of the new office building, through which the outgoing feeders pass at the end of the cable subway.

It is the intention to operate the 21 generators normally in four independent groups, but the interconnections are so arranged that they may all be operated in parallel if desired, or any one generator may be thrown on any group. These connections are indicated in Fig. 10.

The feeder circuit-breakers will be operated by time limit relays having an attachment devised by Mr. W. K. Gibboney of the Power Company. A time limit relay is a useful device for

preventing a circuit-breaker from opening unnecessarily at times of momentary overloads, but if a real short-circuit occurs, it is objectionable. Experience has shown that on a system like that at Niagara, where there is a large amount of syn-

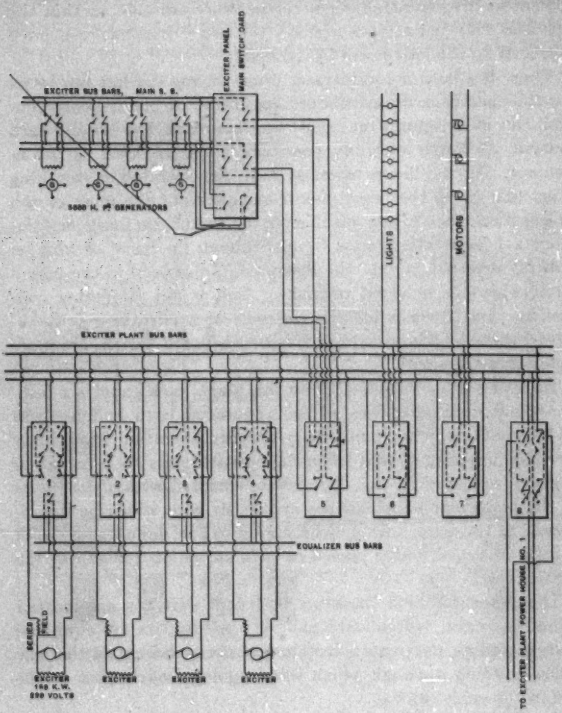

FIG. 8.—Wiring Diagram, Exciter Plant Power-House No 2.

chronous apparatus in operation, if a short-circuit occurs it must be disconnected at once, or else the prolonged drop in voltage will cause all of the synchronous apparatus to drop out of step; whereas, if the short-circuit can be disconnected instantly, the inertia of the rotating parts of the synchronous apparatus will

keep them in step for this short period. For this reason, the ordinary time limit relay is objectionable, since it causes a delay. The device referred to above consists of a dash-pot attachment to the tripping plunger of the circuit-breaker. This retards the movement of the plunger and consequently the opening of the breaker for ordinary temporary overloads, but if a real short-circuit occurs the pull on the plunger is so strong that the dash pot has no effect and the circuit-breaker opens instantly.

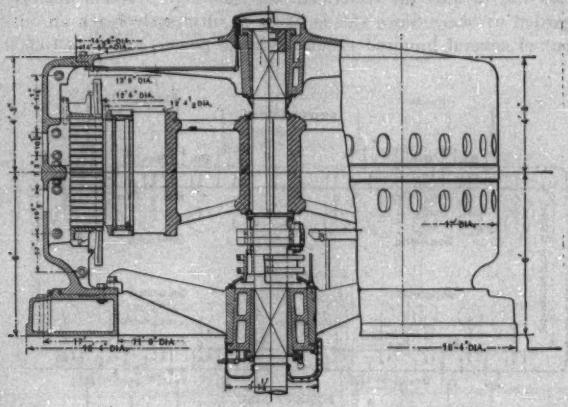

FIG. 9.—10,000-H.P., 12,000-Volt, 3-Phase Generator, Canadian Power-House.

THE CANADIAN PLANT.

Anticipating still further increase in the use of Niagara power, the Niagara Falls Power Company has, through its allied company, the Canadian Niagara Power Company, started work on its plant on the Canadian side of the Falls. This plant will be located in the Victoria Park about 1,500 feet above the Horse Shoe Falls. Its hydraulic feature will be similar to the American plants, with its intake canal, wheel-pit and discharge tunnel leading to the foot of the Horse Shoe Falls. This power development will be used for the transmission of power to Toronto and other Canadian cities within transmission distance, and for the distribution of power to factories located in Canada in the neighborhood of the power-house. It will also be used for the

supply of power to the American power system, with which it will be arranged to operate in parallel.

The essential difference embodied in this plant will be in the size of unit and in the electrical arrangements. The unit will be of 10,000 h.p. capacity (7,500 k.w.), and the generators will be wound for 12,000 volts three-phase. The frequency will be retained at 25 cycles for the sake of uniformity with the American plants, so as to permit of parallel operation. In selecting this size of unit the American and Canadian systems were regarded as one. Since this is likely to ultimately reach an output of several hundred thousand horse power, a unit of 10,000

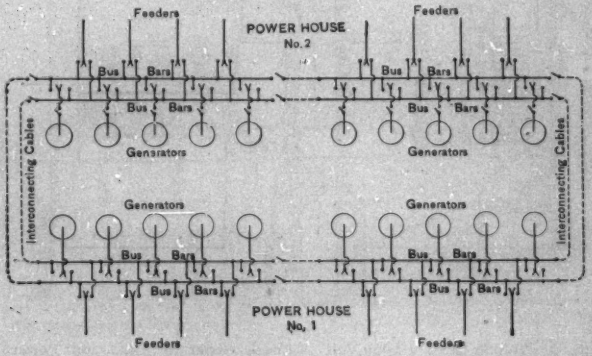

FIG. 10.—Showing Interconnection between American Power-Houses.

h. p. is not a large proportion of the whole and is not too large an amount of power to concentrate in one machine from the standpoint of convenience.

The principal advantage of a unit of this size over the smaller one is in the reduction in cost of development per h.p. This reduction in cost results from

(1) Lower cost of generator per h.p.

(2) Lower cost of turbines per h.p.

(3) A 10,000 h.p. unit occupies only slightly more space than one of 5,000 h.p. capacity which results, for a given plant output, in great reduction in length of wheel-pit, power-house and forebay and a consequent reduction in construction.

Other advantages will result, such as simplicity of operation, owing to the reduction in the number of units and reduction in the cost of maintenance. This size of unit was suggested by the engineers of the Niagara Falls Power Company and was adopted upon their recommendation. The generators, three of which

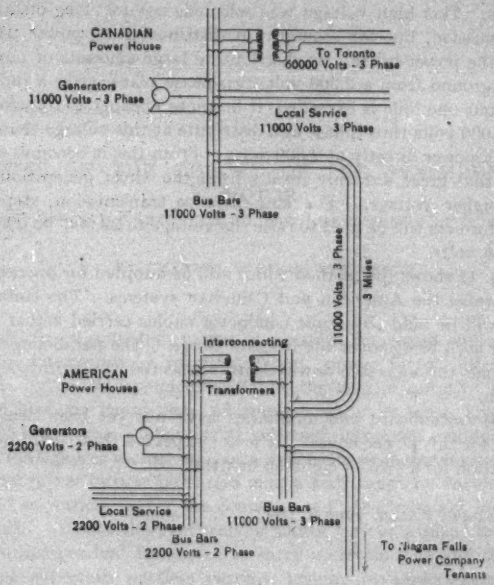

FIG. 11.—Method of Interconnecting American and Canadian Power Systems

have been ordered, are being constructed by the General Electric Company.

This generator is shown in assembly in Fig. 9. It is of the internal revolving-field vertical shaft type. Its revolving-field ring is built up of punched laminations bolted together with joints lapped. This method of construction gives a uniform and definite strength of ring and high magnetic permeability. On account of the high speed, 250 r.p.m., the generator is very small

as compared with some of the large engine-driven units, its over-all diameter being only about 19 feet. The weight of the revolving part of the machine is 141,000 lbs., with a fly-wheel effect at 250 r.p.m. of 2,000,000,000.

The generators are wound directly for 12,000 volts three-phase instead of 2,300 volts two-phase, as in the American plants. This high voltage was selected, not for long-distance transmission, but for economy in distribution to power users near the power-house. In distributing large amounts of power underground from a 2,300 volt, two-phase plant, after a radius of about one mile is exceeded, it becomes cheaper to transform to 12,000 volts three-phase and distribute at this voltage than to supply power directly at 2,300 volts. From this it becomes evident that great economy results from the direct generation of the higher voltage. For long-distance transmission, step-up transformers will be used to raise the voltage to 22,000, 40,000 or 60,000 volts.

Fig. 11 shows the method which will be adopted for operating in parallel the American and Canadian systems. The connection will be made by triple conductor cables carried across the upper arch bridge over the Niagara Gorge. The paralleling will be done through step-down Scott connected transformers, as shown.

The switchboard and auxiliaries have not yet been decided upon for this power-house. It is not expected that it will be in operation for a year or eighteen months.

NIAGARA FALLS, June 6, 1902.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 18th, 1902.

NOTES ON THE THEORY OF THE SYNCHRONOUS MOTOR,

With Special Reference to the Phenomenon of Surging.

BY CHARLES PROTEUS STEINMETZ.

I.

While an induction motor at constant impressed voltage is fully determined as regards current, power factor, efficiency, etc., by one independent variable, the load or output, in the synchronous motor two independent variables exist, load and field excitation. That is, at constant impressed voltage the current, power factor, etc., of a synchronous motor may at the same power output be varied over a wide range by varying the field excitation, that is, the counter e.m.f. or "nominal induced e.m.f." Hence the synchronous motor may be utilized to fulfill two independent functions, to carry a certain load and to produce a certain wattless current, lagging by under-excitation, leading by over-excitation. Synchronous motors are, therefore, to a considerable extent used to control the phase relation and thereby the voltage, in addition to producing mechanical power.

The same applies to synchronous converters.

With given impressed e.m.f., field excitation or counter e.m.f. corresponding thereto, and load, determine by the usual theory all the quantities of the synchronous motor, as current, power factor, etc. Thus, if in diagram Fig. 1, $\overline{OE} = e$ = e.m.f. consumed by the counter e.m.f. of the synchronous motor as corresponding to its field excitation, and if P_0 = output of motor (exclusive of friction and core loss and, if the exciter is driven by the motor, power consumed by the exciter), $i_1 = P_0/e$ =

energy component of current, represented by $\overline{O I_1}$, and the current vector therefore must terminate on a line i perpendicular to $\overline{O I_1}$. If, then, r = resistance and x = reactance of the circuit between counter e.m.f. e and impressed e.m.f. e_0, $\overline{O E_r} = i_1 r$ = e.m.f. consumed by resistance, $\overline{O E_x} = i_1 x$ = e.m.f. consumed by reactance of the energy current i_1, hence $\overline{O E'_1}$ = e.m.f. consumed by impedance of the energy current i_1, and the impedance voltage of the total current lies on the perpendicular e^1 on $\overline{O E_1}^1$. Producing $\overline{O E_1} = \overline{O E}$, and drawing an arc with the impressed e.m.f. e_0 as radius and E_1 as center, the point of intersection with e^1 gives the impedance voltage $\overline{O E^1}$, and corresponding thereto the current $\overline{O I} = i$; and completing the parallelogram $O E E_0 E^1$ gives the impressed e.m.f. $\overline{O E_0}$.

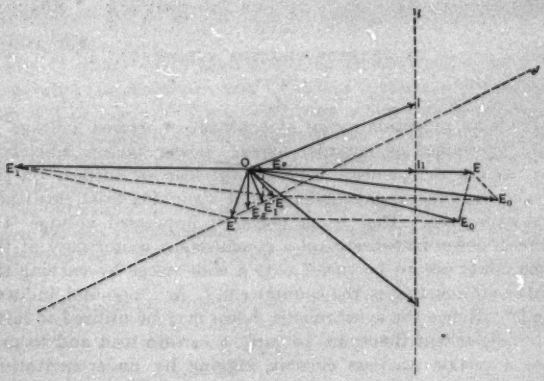

FIG. 1.

Hence, by impressed e.m.f. e_0, counter e.m.f. e, and load P_0 the polar diagram is determined, and thereby the vectors $\overline{O I}$ = current, $\overline{O E_0}$ = impressed e.m.f., $\overline{O E}$ = counter e.m.f., and their phase relation.

Or, in symbolic representation, let:

$E_0 = e_0^1 + j e_0'' =$ impressed e.m.f.; $e_0 = \sqrt{e_0'^2 + e_0''^2}$ (1)

$E = e' + j e'' =$ e.m.f. consumed by counter e.m.f.; $e = \sqrt{e'^2 + e''^2}$ (2)

$I = i =$ current, assumed as zero vector.

$Z = r - j x =$ impedance of circuit between e_0 and e.

Z is the synchronous impedance of the motor, if e_0 is its terminal voltage. It is the impedance of transmission line with transformers and motor, if e_0 is terminal voltage of generator, and Z is synchronous impedance of motor and generator, plus impedance of line and transformer, if e_0 is the nominal induced e.m.f. of the generator (corresponding to its field excitation).

It is, then:

$$E_0 = E + iZ \tag{3}$$

or:

$$e_0' + je_0'' = e' + je'' + ir - jix \tag{4}$$

and, resolved:

$$\begin{cases} e_0' = e' + ir & (5) \\ e_0'' = e'' - ix & (6) \end{cases}$$

The power output of the motor (inclusive of friction and core loss, and, if the exciter is driven by the motor, power consumed by exciter) is current times energy component of induced e.m.f., or:

$$P_0 = e'i \tag{7}$$

Hence, the calculation of the motor from power output P_0, occurs by the equation:

Chosen: i = current.

$$(7)\quad e' = P_0/i$$

$$(5)\quad e_0' = e' + ir$$

$$(1)\quad e_0'' = \pm\sqrt{e_0^2 - e_0'^2}$$

$$(6)\quad e'' = e_0'' + ix$$

$$(2)\quad e = \sqrt{e'^2 + e''^2}$$

That is, at given power P_0, to every value of current i correspond two values of the counter e.m.f. e (and hence the field excitation).

For illustration are plotted in Fig. 2, curves giving the current i as function of the counter e.m.f. e, at constant power P_0, the so-called "synchronous motor phase characteristics," for the values:

e_0 = 2,200 volts

Z = $1 - 4j$ ohms

and; P_0 = 20, 200, 400, 600, 800, 1,000 k.w. output.

The five equations of the synchronous motor:

$$(1)\quad e_0^2 = e_0'^2 + e_0''^2$$

$$(2)\quad e^2 = e'^2 + e''^2$$

$$(7)\quad P_0 = e' i$$

$$(5)\quad e_0' = e' + i r$$

$$(6)\quad e_0'' = e'' - i x$$

determine the five quantities: e_0', e_0'', e', e'', e, as functions of P_0 and i.

The condition of zero phase displacement, or unity power factor at the impressed e.m.f. e_0, is:

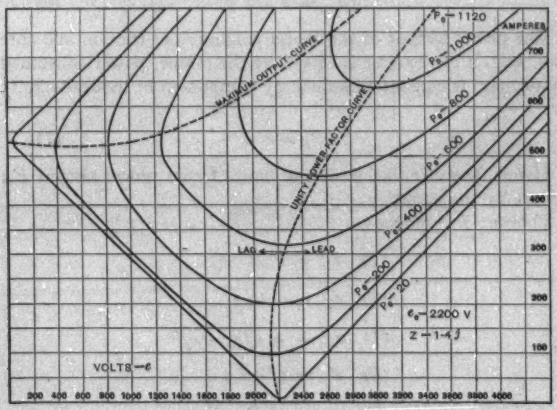

FIG. 2.

$$e_0'' = 0$$

hence: $$e_0' = e_0, \text{ and}$$

$$(6)\quad e'' = i x$$

$$(5)\quad e' = e_0 - i r$$

hence:

$$e^2 = (e_0 - i r)^2 + i^2 x^2 \qquad (8)$$

a quadratic equation, the hyperbola of unity power factor, shown as dotted line in Fig. 2.

In this case, the power is found by substituting $e' = e_0 - i r$ in $P_0 = e' i$, as:

$$P_0 = e_0 i - i^2 r \tag{9}$$

or:

$$i = \frac{e_0}{2 r} \left\{ 1 \pm \sqrt{1 - \frac{4 r P_0}{e_0^2}} \right\} \tag{10}$$

As maximum output of the synchronous motor follows herefrom:

$$\sqrt{1 - \frac{4 r P_0}{e_0^2}} = 0$$

in above instance:

$$P_0 = 1{,}210 \text{ k.w. at: } i = 1{,}100 \text{ amps.}$$

The curve of unity power factor (8) divides the synchronous motor phase characteristics into two sections, one, for lower e, with lagging, the other with leading current.

The study of these phase characteristics, Fig. 2, gives the best insight into the behavior of the synchronous motor under conditions of steady operation.

Of special interest are the load curves of the synchronous motor, or curves giving, at constant excitation: e = constant, the current, power factor, efficiency and apparent efficiency as function of the load or output $P = P_0 -$ (friction + core loss + excitation). Such load curves are represented in Figs. 3, 4, 5, 6, 7 for e = 1,600, 2,800, 2,000, 2,400, 2,180 volts. They are derived from Fig. 2 as the intersection of the curves P_0 = constant with the vertical lines e = constant.

Hence, while an induction motor has one load curve only, a synchronous motor has an infinite series of load curves, depending upon the value of e.

As seen, for low values of e (e = 1,600, under excitation, Fig. 3), the load curves are similar to those of an induction motor. The current is lagging, the power factor rises from a low initial value to a maximum, and then falls again. With increasing excitation (e = 2,000, Fig. 5) the power factor curve rises to values beyond those available in induction motors, approaches and ultimately touches unity, and with still higher excitation (e = 2,180, Fig. 7) two points of unity power factor exist, at P = 20 and P = 450 k.w. output, which are separated by a range with leading current, while at very low and very high load

FIG. 3.

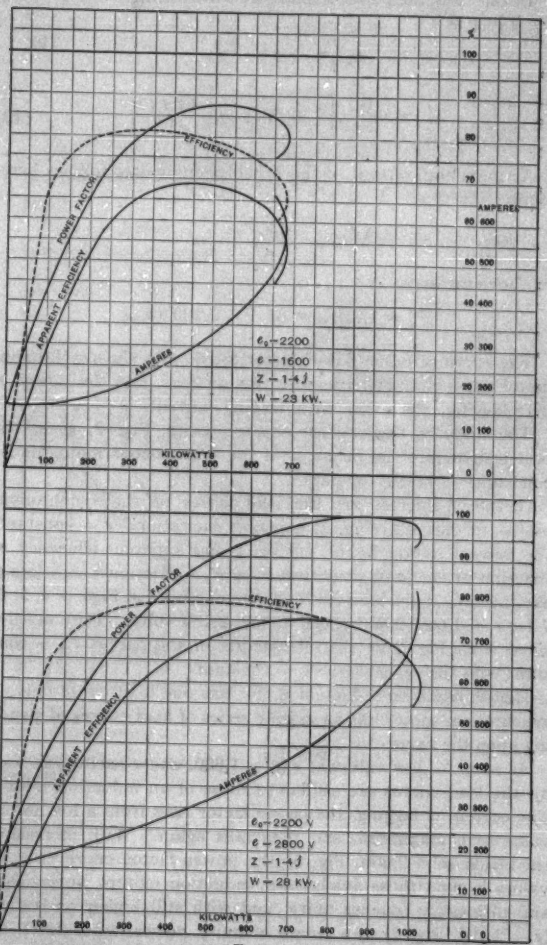
%
EFFICIENCY
POWER FACTOR
APPARENT EFFICIENCY
AMPERES
AMPERES
$e_0 = 2200$
$e = 1600$
$Z = 1 - 4j$
$W = 23$ KW.
KILOWATTS
100 200 300 400 500 600 700
POWER FACTOR
EFFICIENCY
APPARENT EFFICIENCY
AMPERES
$e_0 = 2200$ V
$e = 2800$ V
$Z = 1 - 4j$
$W = 26$ KW.
KILOWATTS
100 200 300 400 500 600 700 800 900 1000

FIG. 4.

the current is lagging. The first point of unity power factor moves toward $P = O$, and then disappears, that is, the current becomes leading already at no load, and the second point of unity power factor moves with increasing excitation toward higher loads, from $P = 450$ k.w at $e = 2{,}180$ in Fig. 7, to $P = 700$ k.w. at $e = 2{,}400$ and $P = 900$ k.w. at $e = 2{,}800$, while the power factor and thereby the apparent efficiency decrease at light loads. The maximum output increases with the increase of excitation and almost proportionally thereto.

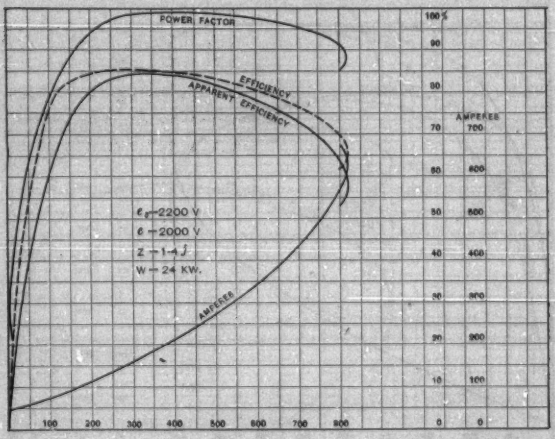

FIG. 5.

It is interesting that at $e = 2{,}180$, the power factor is practically unity over the whole range of load up to near the maximum output. It is shown once more in Fig. 7 with increased scale of the ordinates. A synchronous motor at constant excitation can, therefore, give practically unity power factor for all loads.

The resistance $r = 1$ ohm is assumed so as to represent a synchronous motor inclusive of transmission line, with about 9% loss of energy in the line at 400 k.w. output.

The friction and core loss are assumed as 20 k.w., the excitation as 4 k.w. at $e = 2{,}000$.

Considering the intersections of a horizontal line with the

constant power curves of Fig. 2, gives the characteristic curves of the synchronous motor when operating on constant current. Such curves are shown for $i = 300$ in Fig. 8. They illustrate that at the same impressed voltage with the same current input, the power output of the synchronous motor may vary over a wide range, and also that for each value of power output two points exist, one with lagging, the other with leading current.

As regards phase characteristics and load characteristics, the same applies to the synchronous converter as to the synchronous motor, except that in the former the continuous cur-

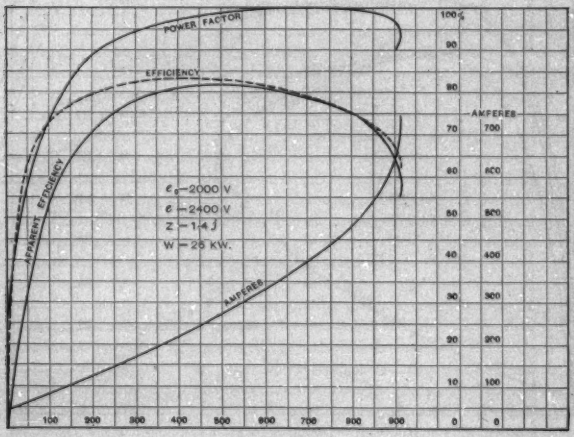

FIG. 6.

rent output affords a means of automatically varying the excitation with the load.

II.

In the preceding theory of the synchronous motor the assumption has been made that the mechanical output of the motor equals the power developed by it. This is the case only if the motor runs at constant speed. If, however, it accelerates, the power input is greater, if it decelerates, less than the power output, by the power stored in and returned by the momentum. Obviously, the motor can neither constantly accelerate nor

decelerate, without breaking out of synchronism, since the counter e.m.f. e must remain within a quarter wave of the impressed e.m.f. e_0, assuming the latter as of constant frequency.

If, for instance, at a certain moment the power produced by the motor exceeds the mechanical load (as, for instance, in the moment of throwing off a part of the load), the excess power is

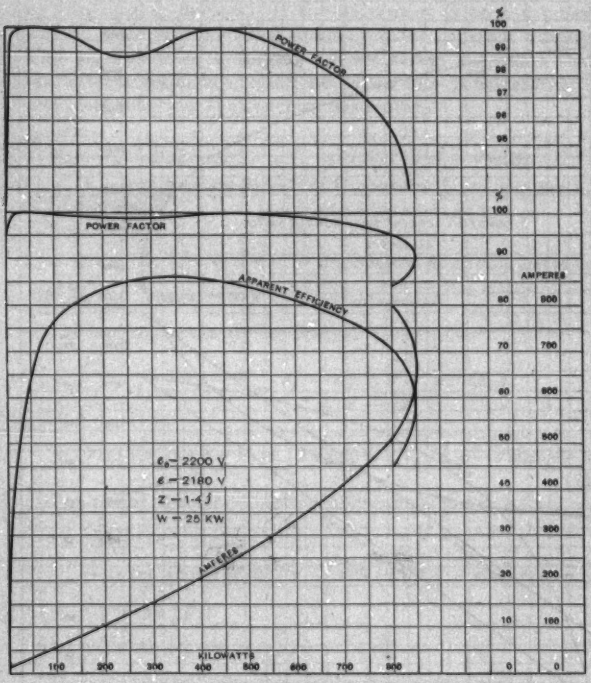

FIG. 7.

consumed by the momentum as acceleration, causing an increase of speed. The result thereof is that the phase of the counter e.m.f. e is not constant, but the vector e (in Fig. 1) moves backward to earlier time, or counter-clockwise, at a rate depending upon the momentum Thereby the current changes

and the power developed changes and decreases. As soon as the power produced equals the load, the acceleration ceases, but the vector e still being in motion, due to the increased speed, further reduces the power, causing a retardation and thereby a decrease of speed, at a rate depending upon the mechanical

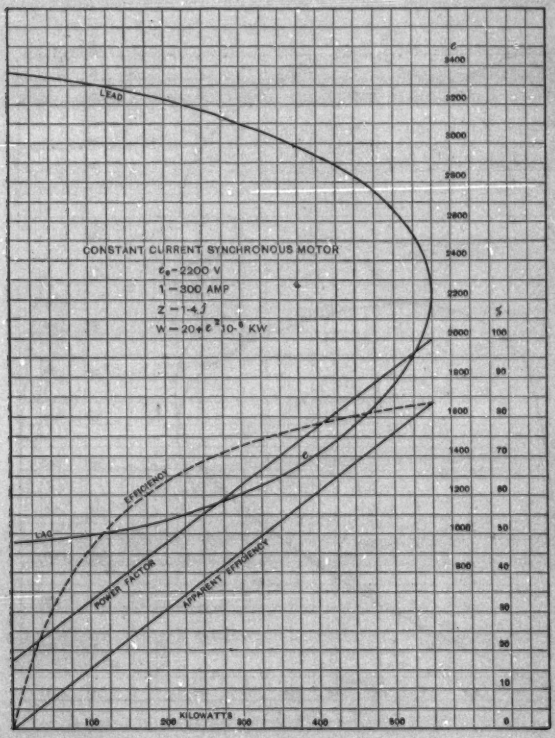

FIG. 8.

momentum. In this manner a periodic variation of the phase relation between e and e_0, and corresponding variation of speed and current occurs, of an amplitude and period depending upon the circuit conditions and the mechanical momentum.

If the amplitude of this pulsation has a positive decrement, that is, is decreasing, the motor assumes after a while a constant position of e regarding e_0, that is to say, its speed becomes uniform. If, however, the decrement of the pulsation is negative, an infinitely small pulsation will continuously increase in amplitude, until the motor is thrown out of step,or the decrement becomes zero, by the power consumed by forces opposing the pulsation, as anti-surging devices. If the decrement is zero, a pulsation started once will continue indefinitely at constant amplitude. This phenomenon, a surging by what may be called electro-mechanical resonance, must be taken into consideration in a complete theory of the synchronous motor.

Let:

$E_0 = e_0$ = impressed e.m.f., assumed as zero vector.

$E = e(\cos\beta + j\sin\beta)$ = e.m.f. consumed by counter e.m.f. of motor where β = phase angle between E_0 and E.

Let:

$Z = r - jx$, $z = \sqrt{r^2+x^2}$ = impedance of circuit between E_0 and E, and: $\tan\alpha = x/r$

The current in the system is:

$$I_0 = \frac{e_0 - E}{z} = \frac{e_0 - e\cos\beta - je\sin\beta}{r - jx}$$

$$= (1/z)\{[e_0\cos\alpha - e\cos(\alpha+\beta)] + j[e_0\sin\alpha - e\sin(\alpha+\beta)]\} \quad (11)$$

The power developed by the synchronous motor is:

$$P_0 = [E\,I]$$

$$= (e/z)\{[\cos\beta[e_0\cos\alpha - e\cos(\alpha+\beta)] + \sin\beta[e_0\sin\alpha - e\sin(\alpha+\beta)]\}$$

$$= (e/z)\{[e_0\cos(\alpha-\beta) - e\cos\alpha]\} \quad (12)$$

If, now, a pulsaton of the synchronous motor occurs, resulting in a change of the phase relation β between the counter e.m.f. e and the impressed e.m.f. e_0 (the latter being of constant frequency, thus constant phase), by an angle δ ,where δ is a periodic function of time, of a frequency very low compared with the impressed frequency, then the phase angle of the counter e.m.f. e is: $\beta+\delta$; and the counter e.m.f. is:

$$E = e\{\cos(\beta+\delta)+j\sin(\beta+\delta)\}$$

hence the current:

$$I = (1/z)\{[e_0\cos\alpha - e\cos(\alpha+\beta+\delta)] + j[e_0\sin\alpha - e\sin(\alpha+\beta+\delta)]\}$$

$$= I_0 + \frac{2e}{z}\sin\frac{\delta}{2}\left\{\sin(\alpha+\beta+\frac{\delta}{2}) - j\cos(d+\beta+\frac{\delta}{2})\right\} \quad (13)$$

the power:

$$P = e/z\{e_0\cos(\alpha-\beta-\delta) - e\cos\alpha\}$$

$$= P_0 + \frac{2ee_0}{z}\sin\frac{\delta}{2}\sin(\alpha-\beta-\frac{\delta}{2}) \quad (14)$$

Let now:

v_0 = mean velocity (linear, at radius of gyration) of synchronous machine

s = slip, or decrease of velocity, as fraction of v_0, where s is a (periodic) function of time; hence:

$v = v_0(1-s)$ = actual velocity, at time t.

During the time element dt, the position of the synchronous motor armature regarding the impressed e.m.f. e_0, and thereby the phase angle $\beta+\delta$ of e, changes by:

$$d\delta = 2\pi N s\, dt$$

$$= s\, d\varphi \quad (15)$$

where: $\varphi = 2\pi N t$

and: N = frequency of impressed e.m.f. e_0

Let:

m = mass of revolving machine elements, and

$M_0 = \frac{1}{2} m v_0^2$ = mean mechanical momentum, reduced to joules or watt-seconds, then the momentum at time t and velocity $v = v_0(1-s)$ is:

$$M = \tfrac{1}{2} m v_0^2 (1-s)^2$$

and the change of momentum during the time element dt is:

$$\frac{dM}{dt} = -m v_0^2 (1-s)\frac{ds}{dt}$$

hence, for small values of s:

$$\frac{d\,M}{dt} = -\,m\,v_0^2\frac{ds}{d\varphi}\,\frac{d\varphi}{dt}$$

$$= -\,2\,M_0\frac{d\,s}{d\,\varphi}\,\frac{d\,\varphi}{dt} \qquad (16)$$

since:

$\frac{d\varphi}{dt} = 2\pi N$, and from (15):

$$s = \frac{d\,\delta}{d\,\varphi}$$

$$\frac{d\,s}{d\,\varphi} = \frac{d^2\delta}{d\varphi^2}$$

it is:

$$\frac{d\,M}{dt} = -\,4\,\pi\,N\,M_0\frac{d^2\,\delta}{d\,\varphi^2} \qquad (17)$$

Since, as discussed, the change of momentum equals the difference between produced and consumed power, the excess of power being converted into momentum, it is:

$$P - P_0 = \frac{d\,M}{dt} \qquad (18)$$

and, substituting (14) and (17):

$$\frac{e\,e_0}{z}\sin\frac{\delta}{2}\sin\left(\alpha - \beta - \frac{\delta}{2}\right) + 2\,\pi\,N\,M_0\frac{d^2\,\delta}{d\,\varphi^2} = 0 \qquad (19)$$

Assuming δ as a small angle, that is, considering only small oscillations, it is:

$$\sin\frac{\delta}{2} = \frac{\delta}{2}$$

$$\sin\left[\alpha - \beta - \frac{2}{\delta}\right] = \sin(\alpha - \beta)$$

hence, substituted in (18):

$$\frac{e\,e_0}{z}\,\delta\sin(\alpha - \beta) + 4\,\pi\,N\,M_0\frac{d^2\,\delta}{d\,\varphi^2} = 0 \qquad (20)$$

and, substituting:

$$a = \frac{e\,e_0\sin(\alpha - \beta)}{4\,\pi\,N\,z\,M_0} \qquad (21)$$

it is:

$$a\,\delta + \frac{d^2\,\delta}{d\,\varphi^2} = 0 \qquad (22)$$

This differential equation is integrated by:

$$\delta = A\,\varepsilon^{C\varphi} \qquad (23)$$

which, substituted in (22) gives:

$$a\,A\,\varepsilon^{C\varphi} + A\,C^2\varepsilon^{C\varphi} = 0$$

$$a+C^2=0$$

$$C=\pm\sqrt{-a} \tag{24}$$

(1) If $a<0$, it is:

$$\delta=A_1\,\varepsilon^{+m\phi}+A_2\,\varepsilon^{-m\phi}$$

where

$$m=\sqrt{-a}=\sqrt{\frac{e\,e_0\sin(\beta-a)}{4\pi N z M_0}}$$

Since in this case, $\varepsilon^{+m\phi}$ is continually increasing, the synchronous motor is unstable. That is, without oscillation it drops out of step, if $\beta>a$

(2) If $a>0$, it is, denoting:

$$n=+\sqrt{a}=+\sqrt{\frac{e\,e_0\sin(a-\beta)}{4\pi N z M_0}}$$

$$\delta=A_1\,\varepsilon^{+jn\phi}+A_2\,\varepsilon^{-jn\phi}$$

or, substituting for $\varepsilon^{+jn\phi}$ and $\varepsilon^{+jn\phi}$ the trigonometric functions:

$$\delta=(A_1+A_2)\cos n\varphi+j\,(A_1-A_2)\sin n\varphi$$

or: $$\delta=B\cos(n\varphi+\gamma) \tag{25}$$

That is, the synchronous motor is in stable equilibrium, when oscillating with a constant amplitude B, depending upon the initial conditions of oscillation, and a period, which for small oscillations gives the frequency of oscillation:

$$N_0=n\,N$$

$$=\sqrt{\frac{N\,e\,e_0\sin(a-\beta)}{4\pi z M_0}} \tag{26}$$

In the instance given in Part I it is:

$e_0=2{,}200$ volts. $Z=1-4j$ ohms, or: $z=4.12$; $a=76°$

Let the machine, a 16-polar 60-cycle 400 k.w. revolving field synchronous motor, have the radius of gyration of 20″, a weight of the revolving part of 6,000 lbs.

The momentum then is: $M_0=850{,}000$ joules.

Deriving the angles β, corresponding to given values of output P and excitation e, from the polar diagram, or from the symbolic representation, and substituting in (26), gives the frequency of oscillation:

$P = 0$:

e = 1600 volts	$\beta = -2°$	N_0 = 2.17	cycles, or	130	periods	per	min.
2180 "	$+3°$	2.50	"	150	"	"	"
2800 "	$+5°$	2.85	"	169	"	"	"
P = 400 k.w.							
e = 1600 volts	$\beta = 33°$	N_0 = 1.90	cycles, or	114	periods	per	min.
2180 "	$21°$	2.31	"	139	"	"	"
2800 "	$22°$	2.61	"	154	"	"	"

As seen, the frequency of oscillation does not vary much with the load and with the excitation. It slightly decreases with increase of load, and it increases with increase of excitation.

In this instance, only the momentum of the motor has been considered, as would be the case for instance in a synchronous converter.

In a direct connected motor-generator set, assuming the momentum of the direct current generator armature equal to 60% of the momentum of the synchronous motor, the total momentum is: M_0 = 1,360,000 joules, hence, at no load:

$P = 0$

e = 1,600 volts:	N_0 = 1.72	cycles, or	103	periods	per	min.
	1.98 "		119	"	"	"
	1.23 "		134	"	"	"

III.

In the preceding discussion of the surging of synchronous machines, the assumption has been made, that the mechanical power consumed by the load is constant, and that no damping or anti-surging devices were used.

The mechanical power consumed by the load varies, however, more or less with the speed, approximately proportional to the speed if the motor directly drives mechanical apparatus, as pumps, etc., and at a higher power of the speed if driving direct current generators, or as synchronous converter, especially when in parallel, with other direct current generators. Assuming, then, in the general case the mechanical power consumed by the load to vary, within the narrow range of speed variation considered during the oscillation, as the p *th* power of the speed, in

the preceding equation instead of P_0 is to be substituted: $P_0 (1-s)^p = P_0 (1-p\,s)$.

If anti-surging devices are used, and even without these in machines in which eddy currents can be induced by the oscillation of slip, in solid field poles, etc., a torque is produced more or less proportional to the deviation of speed from synchronism. This power assumes the form $P_1 = c^2 s$, where c^2 is a function of the conductivity of the eddy current circuit and the intensity of the magnetic field of the machine. c^2 is the power which would be required to drive the magnetic field of the motor through the circuits of the anti-surging device at full frequency, if the same relative proportions could be retained at full frequency as at the frequency of slip s. That is, P_1 is the power produced by the motor as induction machine at slip s. Instead of P, the power generated by the motor, has to be substituted then in the preceding equations the value $P+P_1$.

The equation (18) then assumes the form:

$$P+P_1-P_0(1-p\,s) = \frac{d\,M}{dt}$$

or:

$$(P-P_0)+(P_1+p\,P_0\,s) = \frac{d\,M}{dt} \tag{27}$$

or, substituting (17) and (14)

$$\frac{2\,e\,e_0}{z}\sin\frac{\delta}{2}\sin\left[\alpha-\beta\,\frac{\delta}{2}\right]+(c^2+p\,P_0)\,\frac{d\,\delta}{d\,\varphi}+$$

$$4\,\pi\,N\,M_0\,\frac{d^2\,\delta}{d\,\varphi^2}=0 \tag{28}$$

and, for small values of δ:

$$a\,\delta+2\,b\,\frac{d\,\delta}{d\,\varphi}+\frac{d^2\,\delta}{d\,\varphi^2}=0 \tag{29}$$

$$a=\frac{e\,e_0\sin\alpha-\beta}{4\,\pi\,N\,z\,M_0}$$

$$b=\frac{c^2+p\,P_0}{8\,\pi\,N\,M_0} \tag{30}$$

Of these two terms b represents the consumption, a the oscillation of energy by the pulsation of phase angle β. b and a thus have a similar relation as resistance and reactance in alternating current circuits, or in the discharge of condensers. a is the same term as in part II.

Differential equation (29) is integrated by:
which, substituted in (29) gives:

$$\delta = A\,\varepsilon^{C\phi} \tag{31}$$

$$a\,A\,\varepsilon^{C\phi} + 2\,b\,C\,A\,\varepsilon^{C\phi} + C^2\,A\,\varepsilon^{C\phi} = 0$$

$$a + 2\,b\,C + C^2 = 0$$

which equation has the two roots:

$$C_1 = -b + \sqrt{b^2 - a}$$

$$C_2 = -b - \sqrt{b^2 - a} \tag{32}$$

(1) If: $a < 0$, or negative, that is, $\beta < a$, C_1 is positive and C_2 negative, and the term with C_1 is continuously increasing, that is, the synchronous motor is unstable, and, without oscillation, drifts out of step.

(2) If: $0 < a < b^2$, or a positive, and b^2 larger than a (that is, the energy consuming term very large), C_1 and C_2 are both negative, and, by substituting: $+\sqrt{b^2 - a} = f$, it is:

$$C_1 = -(b - f), \qquad C_2 = -(b + f)$$

hence:

$$\delta = A_1\,\varepsilon^{-(b-f)\phi} + A_2\,\varepsilon^{-(b+f)\phi} \tag{33}$$

That is, the motor steadies down to its mean position logarithmically, or without any oscillation.

$$b^2 < a$$

or:
$$\frac{(c^2 + p\,P_0)^2}{16\,\pi\,N\,M_0} < e\,e_0 \sin\frac{a - \beta}{2} \tag{34}$$

is the condition under which no oscillation can occur.

As seen, the left side of (34) contains only mechanical, the right side only electrical terms.

(3) $$a > b^2.$$

In this case, $\sqrt{b^2 - a}$ is imaginary, and, substituting:

$$g = \sqrt{a - b^2}$$

it is:

$$C_1 = -b + j\,g$$

$$C_2 = -b - j\,g$$

hence:

$$\delta = \varepsilon^{-b\phi}\,[A_1\,\varepsilon^{+jg\phi} + A_2\,\varepsilon^{-jg\phi}]$$

and, substituting the trigonometric for the exponential functions, gives ultimately:

$$\delta = B\,\varepsilon^{-b\phi}\cos(g\,\varphi+\delta) \qquad (35)$$

That is, the motor steadies down with an oscillation of period:

$$N_0 = g\,N$$

$$= \sqrt{\frac{N\,e\,e_0\sin(a-\beta)}{4\,\pi\,z\,M_0} - \frac{(c^2+p\,P_0)^2}{64\,\pi^2\,M_0^2}} \qquad (36)$$

and decrement or attenuation constant.

$$b = \frac{c^2+p\,P_0}{8\,\pi\,N\,M_0}$$

IV.

It follows, however, that under the conditions considered, a cumulative surging, or an oscillation with continuously increasing amplitude, cannot occur, but that a synchronous motor, when displaced in phase from its mean position, returns thereto either aperiodically, if $b^2 > a$, or with an oscillation of vanishing amplitude, if $b^2 < a$. At the worst, it may oscillate with constant amplitude, if $b = 0$.

Cumulative surging can, therefore, occur only if in the differential equation,

$$a\,\delta + 2\,b\,\frac{d\,\delta}{d\,\varphi} + \frac{d^2\,\delta}{d\,\varphi^2} = 0 \qquad (29)$$

the coefficient b is negative.

Since c^2, representing the induction motor torque of the damping device, etc., is positive, and $p\,P_0$ is also positive (p being the exponent of power variation with speed), this presupposes the existence of a third and negative term $\frac{-h^2}{8\pi\,N\,M_0}$ in b:

$$b = \frac{c^2+p\,P_0-h^2}{8\,\pi\,N\,M_0} \qquad (39)$$

This negative term represents a power:

$$P_2 = -h^2\,s \qquad (38)$$

that is, a retarding torque during slow speed, or increasing β, and accelerating torque during high speed, or decreasing β.

The source of this torque may be found external to the motor, or internal, in its magnetic circuit.

External sources of negative P_2 may be, for instance, the magnetic field of a self-exciting direct current generator, driven by the synchronous motor. With decrease of speed, this field decreases, due to the decrease of generated voltage, and increases with increase of speed. This change of field strength, however, lags behind the exciting voltage and thus speed, that is, during decrease of speed the output is greater than during increase of speed. If this direct current generator is the exciter of the synchronous motor, the effect may be intensified.

The change of power input into the synchronous motor, with change of speed, may cause the governor to act on the prime mover driving the generator, which supplies power to the motor, and the lag of the governor behind the change of output gives a pulsation of the generator frequency, of e_0, which acts like a negative power P_2. The pulsation of impressed voltage, caused by the pulsation of β, may give rise to a negative P_2 also.

An internal cause of a negative term P_2 is found in the lag of the synchronous motor field behind the resultant m.m.f. In the preceding discussion, e is the "nominal induced e.m.f." of the synchronous machine, corresponding to the field excitation. The actual magnetic flux of the machine, however, does not correspond to e, and thus to the field excitation, but corresponds to the resultant m.m.f. of field excitation and armature reaction, which latter varies in intensity and in phase during the oscillation of β. Hence, while e is constant, the magnetic flux is not constant, but pulsates with the oscillations of the machine. This pulsation of the magnetic flux lags behind the pulsation of m.m.f., and thereby gives rise to a term in b equation (37). If P_0, β, e, e_0, Z are such that a retardation of the motor increases the magnetizing, or decreases the demagnetizing force of the armature reaction, a negative term P_2 appears, otherwise a positive term.

P_2 in this case is the energy consumed by the magnetic cycle of the machine at full frequency, assuming the cycle at full frequency as the same as at frequency of slip s.

Or inversely, e may be said to pulsate, due to the pulsation of armature reaction, with the same frequency as β, but with a phase, which may either be lagging or leading. Lagging of the pulsation of e causes a negative, leading a positive P_2.

P_2, therefore, represents the power due to the pulsation of e caused by the pulsation of the armature reaction.

Any appliance increasing the area of the magnetic cycle of

pulsation, as short-circuits around the field poles, therefore, increases the steadiness of a steady, and increases the unsteadiness of an unsteady synchronous motor.

In self-exciting synchronous converters, the pulsation of e is intensified by the pulsation of direct current voltage caused thereby, and hence of excitation.

Introducing now the term $P_2 = -h^2 s$ into the differential equations of Part III., gives the additional cases:

$b < 0$, or negative, that is:

$$\frac{c^2 + p P_0 - h^2}{8 \pi N M_0} < 0 \tag{39}$$

Hence, denoting:

$$b_1 = -b = \frac{h^2 - c^2 - p P_0}{8 \pi N M_0}$$

gives:

(4) if: $b_1^2 > a$: $\qquad f = +\sqrt{b_1^2 - a}$

$$\delta = A_1 \varepsilon^{+(b_1+f)\phi} + A_2 \varepsilon^{+(b_1-f)\phi} \tag{40}$$

That is, without oscillation, the motor drifts out of step, in unstable equilibrium.

(5) if: $a > b^2$: $\qquad g = \sqrt{a - b_1^2}$

$$\delta = B \varepsilon^{+ b_1 \phi} \cos(g\varphi + \delta) \tag{41}$$

That is, the motor oscillates, with constantly increasing amplitude, until it drops out of step. This is the typical case of cumulative surging by electro-mechanical resonance.

The problem of surging of synchronous machines, and its elimination, thus resolves into the investigation of the coefficient:

$$b = \frac{c^2 + p P_0 - h^2}{8 \pi N M}$$

while the frequency of surging, where such exists, is given by:

$$N_0 \sqrt{\frac{(N e e_0 \sin(a-\beta)}{4 \pi z_0 M_0} - \frac{(c^2 + p P_0 - h^2)^2}{64 \pi^2 M_0^2}}$$

Case (4), steady drifting out of step, has only rarely been observed.

The avoidance of surging thus requires:

(1) An elimination of the term h^2, or reduction as far as possible.

(2) A sufficiently large term c^2 or

(3) A sufficiently large term $p P_0$.

(1) refers to the design of the synchronous machine and the system on which it operates. (2) leads to the use of electromagnetic anti-surging devices, as an induction motor winding in the field poles, short-circuits between the poles, or around the poles, and (3) leads to flexible connection to a load or a momentum, as flexible connection with a flywheel, or belt drive of the load.

The conditions of steadiness are:

$$\beta < \alpha$$

$$c^2 + p P_0 - h^2 > 0$$

and if:

$$\frac{(c^2 + p P_0 - h^2)^2}{(16 \pi N M_0)} > \frac{e e_0 \sin(\alpha - \beta)}{z}$$

no oscillation at all occurs, otherwise an oscillation with decreasing amplitude.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers Great Barrington, Mass., June 19th, 1902.

A STUDY OF THE HEATING OF RAILWAY MOTORS.

BY A. H. ARMSTRONG.

The electric traction problem presents many new features for investigation which are not met with in steam railroading, and upon which little accurate data has been published. This is especially true of that class of service calling for maximum speeds greater than 35 or 40 m.p.h., where stops are infrequent and cars are run singly or in trains of two cars or more. It is the purpose of this paper to enter into a discussion of some of the variables met with and their influence upon the motive power and station output for the higher as well as the lower speed schedules.

The electrical engineer has to take care of two factors with which the steam engineer is unacquainted, keeping the temperature of the motive power within reasonable limits, and also the operation of single cars at maximum speeds of 60 to 70 m.p.h. That wind friction is a considerable factor with trains operating at high speeds has been abundantly proved by many tests, but these tests are worthless when used to determine the power required to propel a single car at the same high speeds. As the electric motor has invaded the high-speed interurban field and has done so successfully because of the frequency of service furnished with single-car trains, it becomes pertinent to inquire into the size of the motive power necessary to prevent overheating and also the amount of power needed with the high speed schedules and frequent stops made.

Regarding the tractive effort required to propel trains of one or two cars at speeds of 60 m.p.h. or more, there is almost a complete lack of experimental data. Formulæ based upon tests of steam trains made up of a number of heavy coaches

cannot be applied with any accuracy to the operation of single car units. A series of tests made by the General Electric Company on the Buffalo and Lockport tracks, with trains of different sizes, provides almost the only data upon which to base such calculations. These tests were carried up to speeds approaching 60 m.p.h. with ordinary steam railway coaches, hauled by a 38-

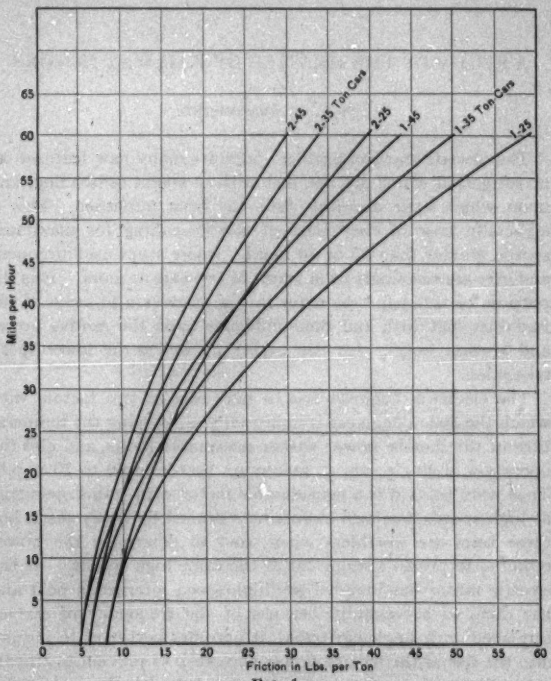

FIG. 1.

ton electric locomotive. The cars were not vestibuled and the conditions were not, therefore, such as to give results directly applicable to the operation of single suburban cars of the vestibule type. For want of more accurate data, these tests will be used as the basis of the following calculations, and, as the curves deduced are used for comparison only, it makes little difference

if the friction values are not absolutely correct These train friction tests were published in the May issue of the *Street Railway Journal*, by Mr. W. J. Davis, Jr., and for convenience of reference some of the curves are here reproduced as Fig. 1.

The tendency of the electric roads has been toward heavier cars, especially on the higher speed lines, where the car weights run from 25 to 45 tons,including equipment and seated passenger load. Suppose we equip cars weighing 25, 35 and 45 tons with the same four-motor equipment, geared for 60 m.p.h. with the 35-ton car, there would then result speed time-curves as in Fig. 2, the speed curve of the 45-ton car falling below and that

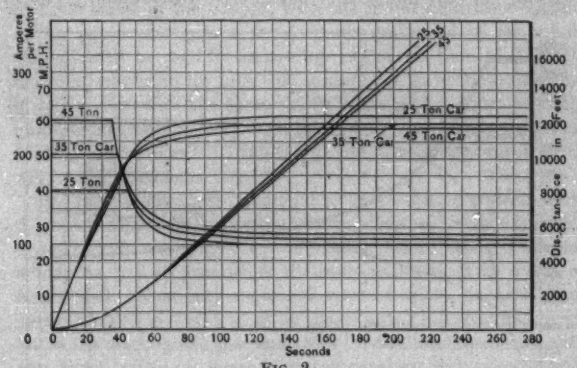

FIG. 2.

of the 25-ton car rising above that of the 35-ton car for the same gear ratio. A tractive effort of 120 lbs. per ton gross has been taken with all three equipments, as representing average conditions for this class of work, giving a net acceleration of about 1.06 m.p.h per second, after deducting friction loss and the power required to accelerate the revolving parts. Any other rate of acceleration could have been taken with little or no effect upon the heating of the motive power or its energy consumption, as will be shown later, the larger part of the energy input being used up in overcoming air resistance at this high speed.

Speed and amperes input are plotted as ordinates with time as abscissa and power may be shut off at any time, the car allowed to coast and brought to rest by brakes, making the enclosed area

of the speed time-curve proportional to the distance covered, and the area of the ampere time-curve equal the ampere hours input. For the sake of simplicity it has been assumed that the friction will be the same at the same speeds during acceleration and coasting; that is, that the energy given up by the rotating parts during coasting will equal the gear and friction loss of the motors running light, an assumption which is approximately correct. The coasting curve will, therefore, follow the shape of the friction curves in Fig. 1, will be curved and show a greater retardation at high than at low speeds.

While power is applied, the motive power has internal losses, varying not only in intensity but in their distribution. At zero

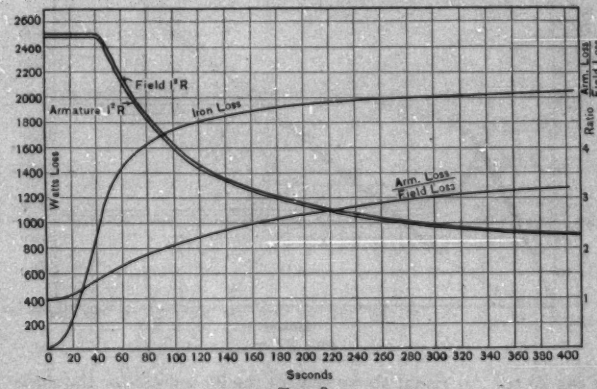

FIG. 8.

speed, the losses are all in the copper of field and armature, being divided according to their relative resistances, but as the armature speed increases there is an iron loss distributed between the iron of armature and pole-face and tips, depending upon the design of the motor. This iron loss starts from zero at standstill and increases to a maximum at the moment of cutting out starting resistances, after which it falls off somewhat, but this again is a matter of motor design. As these various losses are the cause of our motive power heating, it is necessary to trace their influence upon the individual parts of the motor under study.

As the heating of a motor is the result of the average losses within it, the average losses and their distribution up to any

moment of shutting off power must be determined. Such losses are shown in Fig. 3 for our 35-ton car equipment, speed and ampere curves of which are shown in Fig. 2. The motor losses for 25 and 45-ton cars have been left off to avoid confusion, but from the shape of the ampere time-curve in Fig. 2, it is evident that the curves will vary greatly from those shown only during the fractional speed or acceleration period, these differences being virtually wiped out with a considerable amount of running upon the motor curve. Thus, while there is a total average copper loss of 5,000 watts during acceleration upon resistance, the copper loss curve becomes flat in about 400 seconds at the value of 1,800 watts in the copper, with the motor constants chosen. As an equipment geared for a maximum speed of 60 m.p.h. would hardly be used for an average run of less than 15,000 feet, requiring power on for fully 160 seconds for its accomplishment, it will be seen that the acceleration losses play a comparatively unimportant part in very high speed work, so far as the motor heating is concerned. That this is not true of low speed work will be discussed later.

The iron loss has been assumed to be dissipated entirely from the armature in arriving at the " ratio of losses " in Fig. 3. This is not strictly true, but the true subdivision of losses, whatever it may be, will be practically the same with the same ratio of losses, and hence any values of motor heating deduced from curves similar to Fig. 3 must be consistent. For example, if we know the degrees rise per watt loss for field and armature with any given ratio of losses, the temperature arrived at would be correct, provided the temperature constants were obtained from experimental runs where the motor went through the same cycle as in the run to be determined.

Suppose we take our motor equipment, place it upon a car and run it over a measured length of level track, keeping an accurate record of the current input and voltage per motor at each instant. Then let this sample run be repeated successively for a period of ten hours, or long enough for the motor temperatures to reach their maximum, and we have the relation between energy lost in the motor and its temperature for a given set of conditions. Vary the length of the test run and repeat the ten-hour test and we have another relation between temperature rise and energy loss for another set of conditions. It is evident that a series of such tests taken on a given type of motor would give material from which the relation between its internal losses

and temperature rise would be known for any set of conditions, and, moreover, these values could be used directly in calculations for any given service as they were obtained under operative conditions, and need no constant applied to make them approximately correct for service conditions.

It may be urged that it is difficult to reproduce with any accuracy the sample run agreed upon, or that it is difficult to follow through and keep an accurate record of just what takes place in the motor during its cycle of operation. If necessary, an automatic device for applying the current could be used, such as a

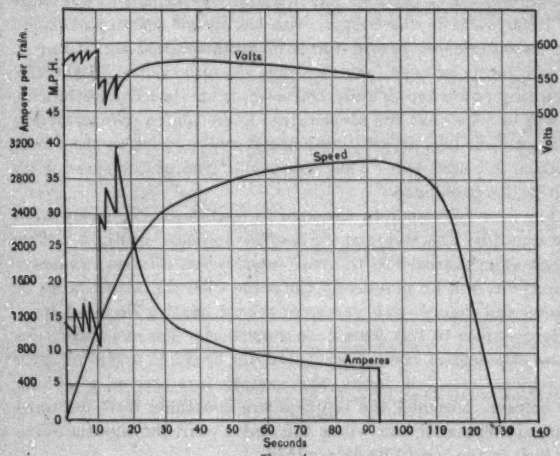

FIG. 4.

motor to throw on the controller at a predetermined speed. Sufficiently good results may be obtained, however, by ordinary hand control with a trained operator, while sample runs taken every few minutes by recording instruments, serve as a check and furnish the material upon which to base the motor's performance during the test.

A sample set of curves of such a test is shown in Fig. 4, indicating voltage, amperes and speed upon a time basis, all taken by recording instruments. The voltage indicated is that between third-rail and ground, but the motor voltage during running upon resistance may be taken as proportional to its full internal

voltage at the moment of cutting out final starting resistance, without making any appreciable error in arriving at iron loss values. The ampere curves give the means of determining the copper losses by plotting on polar coördinates as in Fig. 5, and determining the area by planimeter, giving directly the square root of mean square value. Both Fig. 4 and Fig. 5 show curves produced by a recording instrument placed directly in the main

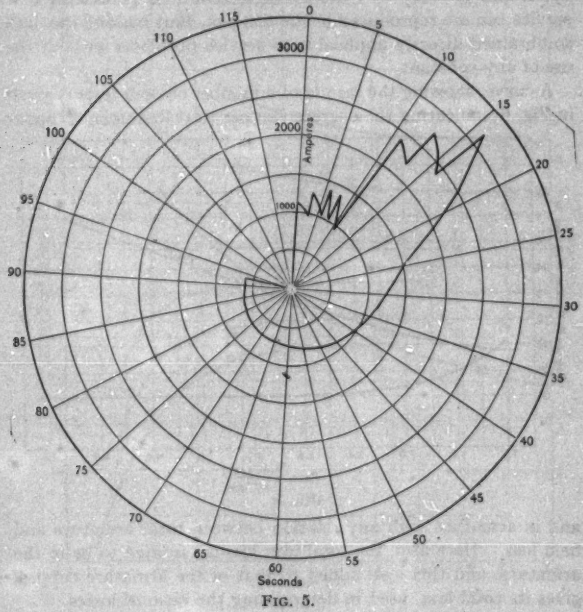

FIG. 5.

circuit of the car, thus giving the series parallel effect of the motors so connected. In our motor calculations we are concerned with the amperes per motor which will be independent of the series parallel control. The curves in Fig. 4 and Fig. 5, however, are shown simply to demonstrate the accuracy of the recording instrument, and while Fig. 5 could not be used directly to determine the square root of mean square current per motor, it shows the method used in determining this constant.

It will be seen that by using recording instruments and by taking a sufficiently large number of curves, it is possible to determine very accurately the average losses dissipated as heat by the motor during the test run, and also to ascertain the distribution of these losses in the several parts of the motor. The motor ventilation is the same as in a service run; it is operated at varying speeds, remains at rest the required proportion of the total cycle, and in every way the average conditions pertaining to a service run are reproduced in the test run, thus making the data so obtained directly applicable to service problems without the use of any constant.

A curve showing the results of a number of such tests is given in Fig. 6, indicating the degrees rise per watt loss in field copper

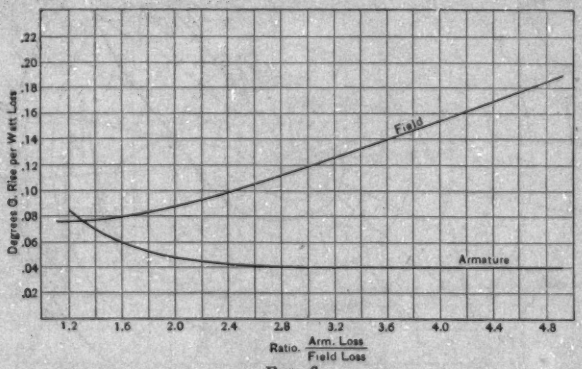

FIG. 6.

and in armature with any relation between total armature and field loss. Here also, the total iron loss is assumed to be in the armature, and this loss, added to that of the armature copper, gives its total loss, used in determining the ratio of losses.

Taking up again the study of the motors mounted upon the 25, 35 and 45-ton cars, we are now in a position to apply the motor losses obtained in Fig. 3 with the 35-ton car, and similar curves with the 25 and 45-ton cars. By completing the cycle in Fig. 2 and bringing the car to rest in any given distance, the time of shutting off power may be determined, the average losses and their distribution ascertained by curves in Fig 3, and the temperature rise found out by applying the constants in Fig. 6. That is, for any given schedule, we may determine the tempera-

ture rise of field and armature for the three-car train weights and the given gear ratio assumed. By plotting a sufficient number of schedules, a curve similar to Fig. 7 will result, which affords a very interesting study.

Such a curve in lieu of a better name might be termed a " service capacity curve " of the General Electric " H " motor. It

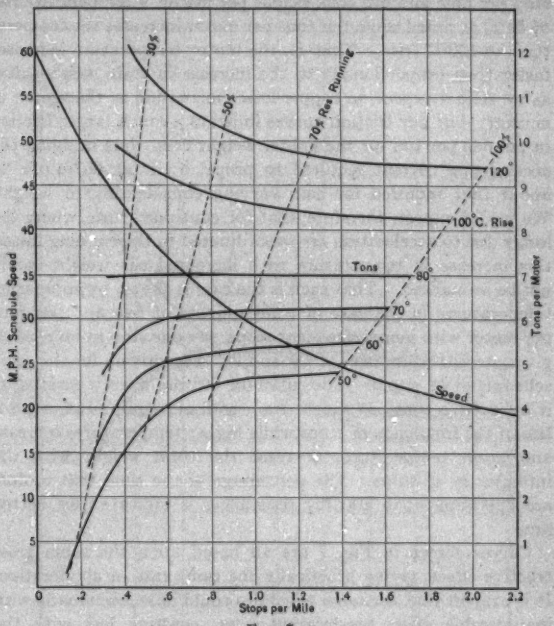

FIG. 7.

shows the temperature rise per motor for any weight of car and the schedule that can be performed with the gear ratio chosen, all plotted in terms of the number of stops per mile. The temperature rise is given as that of the hottest part, whichever it may be. The schedule includes stops lasting 15 seconds each. Acceleration is the result of a constant tractive effort of 120 lbs. per ton during resistance running, and braking is effected at the rate of 150 lbs. per ton. Coasting is assumed to continue 10% of the duration of the running cycle. Curves of higher

temperature cannot be completed without greatly exceeding the commutation limit during acceleration, but would reverse and approach zero the same as those of lower temperature for infrequent stops.

The relation between train weight and temperature rise for a given schedule and frequency of stops is instructive. With one stop per mile and five tons weight per motor, a temperature rise of 54°C. is noted while ten tons per motor increases the temperature to 120°C. rise. That is, the motor temperature increases faster than proportionally to the increase in train weight, due, as we should expect, to copper losses increasing as the square of current; but our friction curves indicate a much larger friction in pounds per ton for the lighter weight cars, thus bringing the accelerating current required to propel a car at 60 m.p.h. to about that required for cars varying considerably in weight. We would expect, therefore, that for continued runs, where the losses due to acceleration are subordinated to the running losses, this increase in temperature with increased car weight would not be so marked. That such is the case is shown by comparing temperatures in the case of train weights of five and ten tons per motor with more infrequent stops, say one stop in four miles, giving temperature rises of 72° and 98° respectively for the same schedule of 48 m.p.h. The curve for 80° rise is very curious, as it indicates a constant weight train with our equipment, regardless of the frequency of stops, while higher temperatures increase and lower temperatures decrease the train weight with the infrequency of stops. The percentage of the time that motors are operating upon starting resistances is indicated by dotted lines.

Curves shown in Fig. 7 are all based upon the same gross tractive effect, giving practically the same rate of acceleration. It is evident that the same schedules could have been made with innumerable other accelerating rates, coasting less with the slower and more with the more rapid rates. In order to make our study of the " H " motor more complete, two sets of curves similar to Fig. 7 were plotted, the first with an accelerating rate of 90 lbs. per ton gross and 10% coasting, and the second with 120 lbs. per ton and 25% coasting, both making the same schedule with the same frequency of stops. The comparison of these two curves is shown in Fig. 8, plotted for a temperature rise of 60° only, in order to avoid confusion. The lower rate and less coasting has some advantage for more frequent stops, but

as such an equipment would not be used geared for 60 m.p.h. with much less than a two mile run average, it follows that the temperature rise would be virtually the same with either rate of acceleration.

Lower speed equipments, however, present results differing from this, as is shown in Fig. 9, illustrating the 60° rise curve for

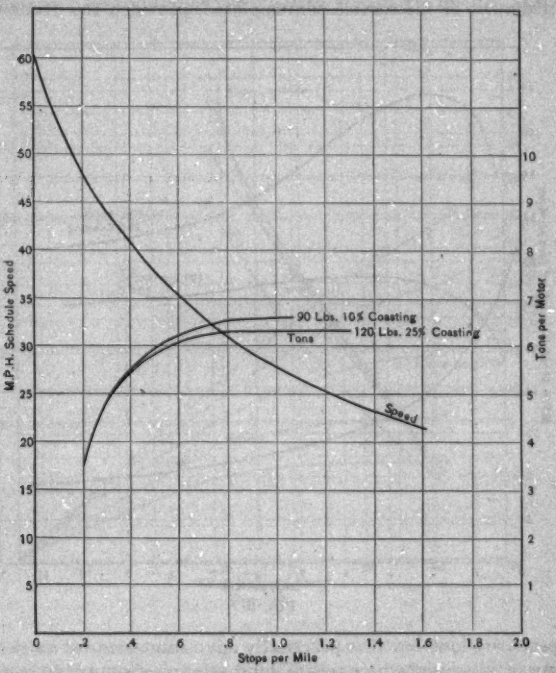

FIG. 8.

a maximum speed equipment of 30 m.p.h. Here 160 lbs. and 25% coasting contrast very favorably with 120 lbs. and 10% coasting. In other words, the motor capacity is greatly increased by raising the accelerating rate while still maintaining the same schedule and frequency of stops. Increasing the

accelerating rate does not necessarily mean going beyond the commutating limit of our motors, as a lower speed gearing can increase the rate of acceleration with the same current flowing in the motors as with the slower rate of a higher speed gearing.

A study of the foregoing curves seems to indicate that, so far as motor heating is concerned, it is preferable to use the largest gear ratio and highest rate of acceleration possible for the accomplishment of the service contemplated, provided the maximum

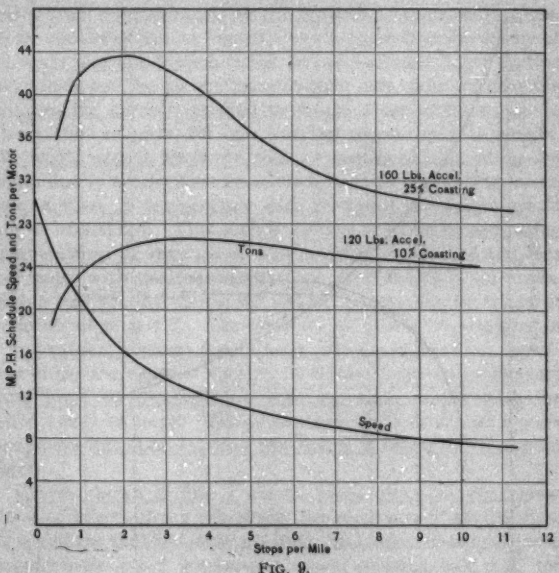

FIG. 9.

speeds are low, but that practically any rational rate of acceleration may be used where speeds approach a maximum of 60 m.p.h. As will be shown later, the energy consumption is less for a higher rate of acceleration permitting more coasting, but unfortunately the fluctuations on the distribution system and the load curve on the generating station may both be much poorer if the accelerating rate is carried too high and the number of units in service is small. In the choice of gear ratio for a given

service, therefore, not only must account be taken of the question of motor heating with different rates of acceleration, but due heed must be paid to the question of line fluctuations, station load and energy input. It may be possible that what is gained in car energy by a more rapid acceleration, may be lost by the poorer coal economy resulting from a more irregular load curve upon the generating station.

So far we have considered the question of capacity of our " H "

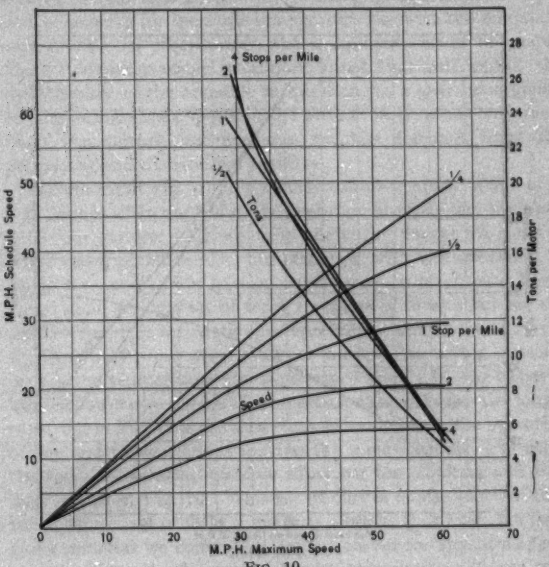

FIG. 10.

motor for one gear ratio only. It is obvious that similar calculations may be made for any other gear ratio corresponding to a different maximum speed on the level, and by combining the results of several sets of such calculations, it is possible to arrive at a capacity of our " H " motor for any schedule, any gear ratio and any frequency of stops. This may be plotted in terms of any temperature rise, and a set of such curves is plotted in Fig. 10 for a temperature rise of 60°. This set of curves still retains

120 lbs. per ton tractive effort, 15-second stops, 150 lbs. braking effort, and is based upon the performance of a single car using a four-motor equipment, following the lines of the friction curves given in Fig. 1. The relation between schedule speed and maximum speed on the level is shown with stops varying from one in four miles to four per mile, and the tons per motor for a maximum temperature rise in any part of the motor of 60° C. are shown from one stop in two miles to four stops per mile.

A careful study of the curves in Fig. 10 gives very interesting

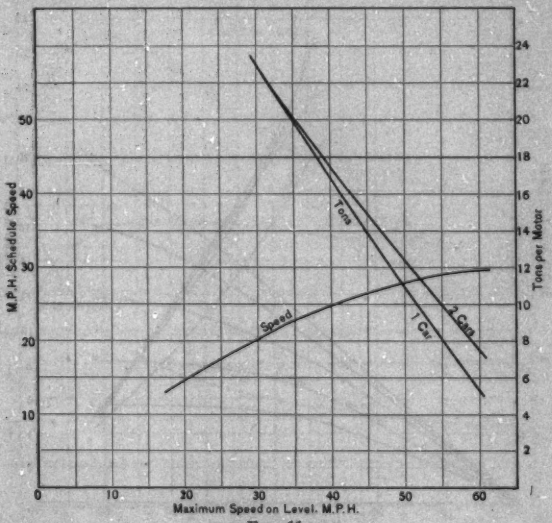

FIG. 11.

results. For instance, the " H " motor geared for 60 m.p.h. can operate between the limits of one stop in two miles and four stops per mile, making a schedule of from 40 m.p.h. down to 14 m.p.h., with approximately five tons per motor in all cases and the same temperature rise. In other words, an equipment of this character is protected from overheating by properly proportioning its gear ratio to the car weight. The possible schedule speed for a given gear ratio is controlled by the number of stops per mile, but the heating of the equipment, with the

proper weight of car, will be the same over a very wide range of schedules and stops. The curves, also, bring out very forcibly the importance of properly gearing an equipment for the work which it has to do. For instance, a gearing giving 60 m.p.h. on a level track can make but 20.5 m.p.h. schedule with two stops per mile with a train weight of 5.6 tons per motor, while the same equipment geared for 47.5 m.p.h. can perform 20 m.p.h. schedule (practically the same), but can do so with a total train weight of 12.8 tons per motor, or more than double the train weight possible for the same temperature rise with the 60 m.p.h. equipment. In other words, the equipment should be geared for the lowest possible maximum speed that will permit the maintenance of the schedule in question, as a gear ratio giving too high a maximum speed for the work to be done not only overheats the motors, but produces needless demands upon the generating and distribution systems.

The curves in Fig. 10 give a fairly complete study of the type "H" motor when applied to the operation of single cars equipped with four motors. All points in the curve, except for a maximum speed of 30 m.p.h., are obtained with the operation of single cars, and as our friction curves may be inaccurate, being based upon a single set of tests, or trains of more than one car may be run, it is instructive to reproduce a similar set of curves for two, three, four cars, etc., per train. The motor capacity for a given temperature rise is governed largely by the shape of the friction curve used at high speeds, especially for the longer runs, and in Fig. 11 is shown a comparison between the operation of one and two-car trains making the same schedule, and using the same accelerating tractive effort per ton, braking and stop intervals as in Fig. 10. This set of curves is also plotted for a temperature rise of 60° C., but it is obvious that from the foregoing material we could plot similiar curves for any other temperature rise. As the curves showing the relation between tons per motor and maximum speed for a given temperature rise come so close together for the different frequency of stops, this sheet has considered only the relation between tons per motor and maximum speed for one stop per mile. Thus we see that at 60 m.p.h. the type "H" motor operating a single car has capacity of but 5.3 tons per motor for 60° rise, while if two cars are coupled together and operated as a single train, the reduction in wind friction per ton of train weight increases the capacity per motor to 7.5 tons for the same 60° temperature rise, an in-

crease of 42%. This opens up a new field of inquiry as to whether it is commercially advisable to run single car units at this high speed when the motive power, and as it will be shown later on, the energy input, are both larger than would result from operating the same seating capacity in trains of two cars or more, with a correspondingly increased time interval between trains. In other words, is the electric traction idea of small units at frequent intervals a proper method of attacking the very high speed electric traction problem, or are we compelled to go back to the steam method of operating heavier trains at more infrequent intervals, in order to prevent a prohibitive investment in motors, and generating and distributing systems, and a ruinous expense for operation? It is true that the electric system, being eminently adapted to subdivision, has created a demand for travel, by means of its frequent service, where none previously existed, but it may be possible that for very high speed work too great a price may be paid for the privilege of operating very frequent small units.

The foregoing discussion has described a method of determining the probable heating of a given motor when operated under any known conditions. The results obtained are so complete and give such a mass of working data directly applicable to service requirements, that the labor of the detailed calculations necessary seems amply justified. Specifications of stationary apparatus are prepared in careful detail and acceptance tests carried out with great exactness, but the tendency to slight the railway motor problem, owing largely to its seeming complexity, is hardly warranted, when it is considered that the capital invested in such apparatus may be double that required for generator power to drive it. Then, too, the generator is carefully housed, provided with an attendant and otherwise taken care of, while the motor is exposed to outside climatic conditions and only gives evidence of being overloaded by burning out. The selection of such apparatus should receive the most careful attention, the proposed service conditions fully worked out and the proper size of motor and correct gearing chosen to ensure a reasonably small expense for maintenance.

The present method of rating railway motors is to determine the current which they will carry at 500 volts on a stand test giving a temperature rise of 75° C. in the hottest part after sixty-minutes' run. In other words, the one-hour rating of railway motors gives only an indication of the comparative capacity of

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two motors in actual service, and affords no data to serve as the basis of calculating the service capacity of the motor. It does determine the mechanical qualities of the motor, as the one-hour test is generally very severe, and it also affords a means of observing commutation at the maximum current for which the motor will probably be called upon in service operation. Some method of rating railway motors which would give an accurate comparison of their service capacity under different conditions, if such a rating is possible, would be of great advantage over the present very general one-hour rating.

The foregoing investigation has pointed out the very variable nature of the work which a railway motor has to do, and the different relations between service performed, distribution of losses and the ultimate heating of the motor. In Fig. 3 the various motor losses are shown for the type " H " motor, taken as an example, but it is evident that different motor loss curves, even for the same service performed, could not be compared directly with any assurance of arriving at their comparative temperature rise. Proceeding further, we come to the values given in Fig. 6, showing the relation between motor losses, their distribution, and the resulting temperature rise per watt loss. Similar curves of different motors could be compared directly and give some means of determining their relative capacity, but here, also, there is no direct comparison, as different motors do not have the same efficiency, and therefore will not give the same loss for the same service performed. In other words, given two motors having the same thermal constants, that is, the same degrees rise per watt loss, the motor having the poorer efficiency will rise to a higher temperature for the same service performed, owing to its greater loss. We cannot, therefore, look to the thermal curves as giving the comparative rating needed.

In Fig. 7 we have a fairly complete history of the type " H " motor operating under a given set of assumptions. These assumptions are those pertaining to service operation, and such a set of curves for another motor calculated for the same conditions would give accurately the comparative size, or in other words, the comparative temperature of the two motors for the same service performed. In Fig. 7, the " service capacity curves " approach much nearer to a basis of comparing different motors, but as a method of rating railway motors it is incomplete. In the first place, we have assumed a given rate of acceleration, while it is obvious that the demands of different

classes of service, especially low-speed service, will call for different rates of acceleration, and hence a separate sheet would have to be made out for every rate of acceleration. The effect of increasing the rate of acceleration and increasing the time of coasting is shown in Fig. 9, giving such discrepancy between tons per motor for a given temperature as to make sheets similar to Fig. 7 entirely unreliable for comparing different motors, especially when the maximum speeds are low and the acceleration energy is the determining factor in the motor heating.

There is another variable, the rate of braking, which has not been entered into in this discussion, and which also affects the heating of the motor, especially on low-speed, high-acceleration problems. On the higher speed problems, where friction is the ruling factor, it is found that we must also assume a certain friction rate, or in fact a friction curve plotted to a definite formula, in order to arrive at consistent results with different motors. Having once determined on this friction curve for a single car, our calculations are immediately disqualified when we couple two of these same cars together and perform the same service, the friction rate at speeds of 50 or 60 m.p.h., falling off considerably as we approach a train composed of several units.

In addition to the foregoing variables, we have the element of the energy consumed by the rotating parts during acceleration. This factor is practically negligible at very high speeds, but figures very prominently in acceleration problems with low speeds. In giving the rating of a railway motor, it will be necessary, therefore, to fix definitely upon the weight and center of gyration of car wheels and armatures, and furthermore to determine the effect of the motor parts for a given gear ratio.

After all these variables are definitely fixed, we must repeat the same set of conditions for each motor gear ratio, or, as a more general case, for each different maximum speed on level, thus eliminating the question of the total number of teeth in gear and pinion. It is not intended in any way to discourage an effort to rate a railway motor by some method that will give its comparative capacity, but it is well to canvass carefully the large field of variables which must enter into such a rating, and to have clearly in mind the bearing which these different variables have in determining the temperature of the motor. It is evident that by affixing certain values to accelerating rate, train friction, braking effort, energy of rotating parts, etc., it will be possible to prepare a set of curves giving the relation between

schedule, frequency of stops and temperature rise for any car weight, which would give accurately the comparative size of a railway motor in relation to any other motor for which curves were similarly plotted. Such work is being done by the General Electric Company on its standard railway motors, and in fact is necessary in order to be able to give the probable performance of a motor under any set of conditions and to follow through the effect of changing the conditions. The method, however, is cumbersome, and has so many factors entering into the case that it probably may never serve as a commercial rating; furthermore, such relation could only be expressed by curves, or a long, tabulated statement, and neither method is short and concise enough for a commercial rating.

As the result of considerable investigation along these lines, the writer has not arrived at any commercial rating of a railway motor which serves its purpose better than the one-hour test now universally used. Admitting that such a test does not give the comparative size of different motors, it does serve the purpose of largely determining its commutating qualities and possesses the advantage of being commercial. Unless a rating can be proposed which will indicate accurately the relative size of motors, the present method of one-hour rating possesses advantages which would hardly warrant its being superseded.

Although insufficient data is at hand from the foregoing calculations to form the basis of a complete treatise on the subject of train energy, sufficient material is provided to furnish some very interesting comparisons. As the basis of calculations, we assume the operation of single car trains composed of 25, 35 and 45-ton cars, geared for a maximum speed of 60 m.p.h. for the 35-ton car. From our friction curves we find that these three cars at 60 m.p.h. require a tractive effort of 59 lbs., 50 lbs. and 43.5 lbs. per ton respectively. The same calculations were carried through for trains composed of two cars or more, the cars being of different weights, so that we were able to plot a set of curves showing the relation between schedule speed and watt hours per ton mile input to the train, virtually ignoring any fixed formula for train friction. Such a set of curves is shown in Fig. 12, being plotted for 30, 40, 50 and 60 lbs., per ton friction rate at 60 m.p.h. These curves may be regarded as fairly general in their scope, except that they follow the general form of the friction curves given in Fig. 1. In other words, we can get from these curves in Fig. 12, the energy consumption for any friction rate at

60 m.p.h., the error introduced by assuming a general shape of curve being very small.

An inspection of Fig. 12 brings out forcibly the fact that the subject of car energy at high speed is most intimately interlinked with the question of train friction. As the schedule speed decreases with the increasing number of stops, or in other words, as the energy of acceleration becomes a more important factor, the per cent difference between the energy values for different train frictions becomes less, as would be expected.

The electric road has almost universally used one car units, and as it has branched out into suburban high speed work, the

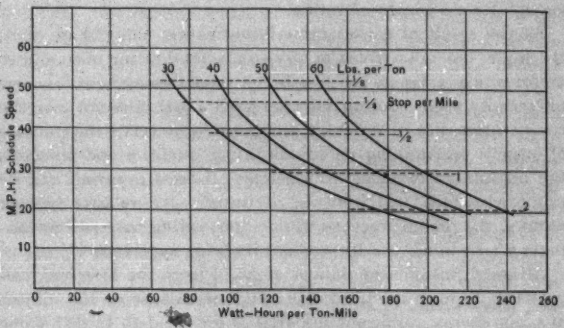

FIG. 12.

advantages of more frequent service have made the operators of such roads retain the single car idea. From the curves given in Fig. 12, some figures may be secured of what it costs to operate a single car, and also trains of two or more cars, where the maximum speed is 60 m.p.h., and the stops very infrequent; that is, the more advanced type of our private right-of-way suburban road. A single 35-ton car having a friction, say, of 50 lbs. per ton at 60 m.p.h., will consume 119 watt hours per ton mile at a schedule of 52 m.p.h. with one stop in eight miles. Let two such cars be coupled together in a train, reducing the friction to 33.5 lbs. per ton, and the train will require an input of only 78 watt hours per ton mile, or 65.5% of the energy rate per ton required in single car operation. In other words, single cars on 30-minute headway would require 52.5% more energy for their operation than would two-car trains on one-hour headway.

With five-car trains composed of 35-ton cars, the energy is reduced to 56 watt hours per ton mile for the same schedule, or less than half what will be required per ton for the operation of single car trains.

From a purely energy standpoint it would seem that the operation of single-car trains was disadvantageous, but experience has shown that it is not fair to assume that two cars operated every hour will attract the same custom as one car operated every thirty minutes. In other words, the frequency of service creates travel and in many cases warrants the extra expenditure for coal. There is another aspect of the case to be considered and that is, that with two-car trains at more infrequent intervals the load upon the feeding points is more fluctuating, the size of

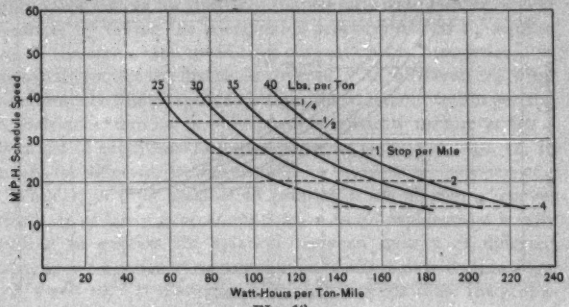

FIG. 13.

rotary converters must be somewhat increased, and in all probability a larger amount of feeder copper will be required to keep the drop within the same limits. Although a saving may be effected in the coal pile by increasing the train headway and giving the same seating capacity in trains of two or more cars, there is every reason to expect a call for a greater expenditure of money to install the road, and an increase in interest and maintenance account that may go far toward eating up the saving in the fuel expense.

In Fig. 13 and Fig. 14 are given curves showing the relation between schedule speed and train energy for maximum speeds of 45 and 30 m.p.h. respectively. It will be noticed that, particularly for 30 m.p.h. maximum speed, the train friction becomes a very much smaller factor in determining the energy input, especially as the number of stops per mile increases.

All these three sets of curves are plotted for an accelerating rate corresponding to 120 lbs. per ton, and a braking effort of 150 lbs. per ton. The values given will, therefore, be subject to considerable variation for different accelerating and braking efforts where the schedule speed is low and stops numerous. The curves are, however, of fairly general use, especially for runs of a mile or more, as the effect of the rate of acceleration and braking is not so marked on longer runs.

In Figs. 12, 13 and 14 is considered, also, a period of coasting equalling 10% of the time the train is in motion. While this is a fairly general assumption and will give sufficient margin

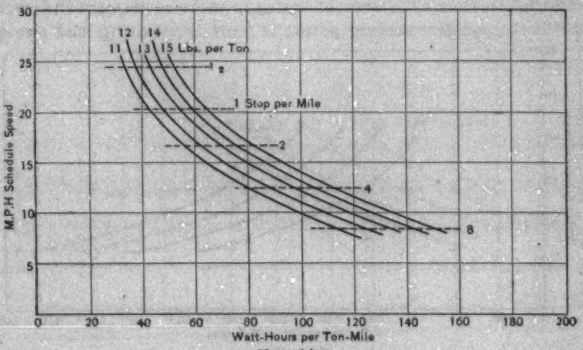

FIG 14.

for a large majority of problems, it will be found in carrying out the subject to a conclusion that the per cent of coasting is a very large factor in determining the train energy input. For instance, a high rate of acceleration with a long period of coasting will demand less energy input to the train than a lower rate and little or no coasting. The reason for this is obviously that the efficiency of acceleration of the two runs may be approximately 70%, while the speed at which brakes are applied is less with a longer coasting period, and hence the work demanded by the equipment is less.

In all three of the energy curves given, a variable friction during acceleration and coasting is considered, but straight line braking is assumed. The energy required to accelerate the rotating parts is also considered, so that the curves as given are of fairly general application.

In this paper the writer has attempted to outline a method of determining the probable heating and energy consumption of a given equipment for any class of work, having in mind, also, the possibility of arriving at some short,concise method of rating different railway motors, so that their comparative service capacity might be accurately indicated. As the subject of motor capacity is so dependent upon experimental tests, not only of car friction and braking, but also of heat radiation under working conditions, the conclusions drawn were based so far as possible upon actual experiments made. Were it not for the fact that car friction, or rather train friction, is such a variable quantity, dependent not only upon the condition of track but upon the speed and composition of the train, it would be possible to plot a set of curves for a given friction and distance, and apply these curves for similarly shaped runs over greater or less distances by taking the coördinates proportional to the square root of the area of the speed time curves; that is, proportional to the square root of the distances covered. As, however, the wind friction at the higher speeds changes the value of friction per ton to such an extent, it is only possible to draw up curves for a given set of conditions and generalize, as is done in Figs. 12, 13 and 14 for different friction rates.

While it is thus possible to prepare a set of energy curves which are of fairly general application to all problems, it is only feasible to express the relation between motors of different capacity by a series of curves similar to those described in Figs. 7, 8, 9 and 10. It is entirely possible to approximate the probable heating of motors of different sizes when the resistance, core loss and general construction are known, but such short-cut methods are at best only approximations and no true comparison of different motors can be made which will take into account their different losses for the same work performed and their capacity for radiating these losses at different speeds, without considering the subject in detail for each motor alone along the general lines indicated in this paper.

In dealing with the railway motor where the temperatures approximate 60° C. rise in practice, with an air temperature in summer reaching 30° to 35° C., we have not much leeway below a temperature injurious to the insulation, and approximate methods giving rise to errors of 10° or 20° C. in temperature cannot be seriously considered in such important calculations as the determination of railway motor temperatures. For this reason

the methods outlined, although entailing a large amount of experimental work and subsequent calculations, provide an accurate method of determining the temperature of railway motors operating under any known conditions, and although they fail to provide a method of rating railway motors, it is due to the fact that such a method of rating cannot be expressed by any short term, but necessitates some such general curves as are indicated in the paper.

The writer wishes to acknowledge the services of Mr. E. F. Gould in preparing material for this paper, and the kindness of the General Electric Company in furnishing results of experimental tests which served as a basis of all calculations.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 19th, 1902.

COMPARATIVE ACCELERATION TESTS WITH STEAM LOCOMOTIVE AND ELECTRIC MOTOR CARS.

BY B. J. ARNOLD AND W. B. POTTER.

In connection with the preparation of a report on the use of electricity for the propulsion of trains of the New York Central Railroad in the tunnel entrance and terminal in New York City, an invitation was extended by the General Electric Company to Mr. W. J. Wilgus, Chief Engineer of the railroad company, to use its experimental track (Fig. 1), and apparatus at Schenectady, and a series of tests were accordingly carried out under the direction of the authors of this paper. The tests were principally for the purpose of determining the comparison between steam and electric traction on short-haul suburban passenger service. Owing to the short curves in the connecting tracks, the General Electric Company's track could not be used for the steam locomotive tests. The steam tests, therefore, were made on the New York Central main line tracks west of Schenectady.

The steam locomotive shown in Fig. 2 was built from the specifications of Mr. A. M. Waite, Superintendent of Motive Power and Rolling Stock of the New York Central, by the Schenectady Locomotive Works. It was designed specially for the rapid acceleration work required in suburban service, being provided with large grate area and heating surface and a very large proportion of weight on its driving wheels.

The two electric motor cars were similar in form, 54 feet over all, each weighing about thirty-five tons including the electrical equipment, which consisted of four "G. E. 55" motors and type M. control. All axles being equipped with motors, the two cars together gave approximately the same weight upon

the drivers as the steam locomotive. The acceleration was, therefore, directly comparable for trains of equal net weight, and to secure this comparison the same trail cars arranged in the same order were used in both the steam and electric tests.

In the steam runs the draw-bar pull, speed and time were recorded by an Illinois Central dynamometer car, and the same car was used with the electric motor cars to determine the relation between current input and draw-bar pull. The dynamo-

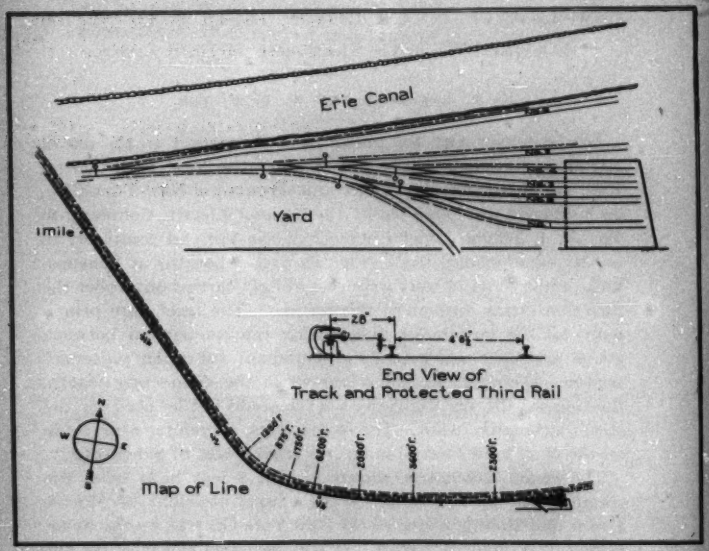

FIG. 1.—Map of General Electric Railroad.

meter car had to be returned before the electric runs were completed, but not before a large number of readings were taken, from which curves were plotted showing the relation between amperes and draw-bar pull with different weights of train behind the motor cars. The draw-bar pull thus determined has been plotted on the attached electric motor car curves, which were taken subsequent to the return of the Illinois Central car.

The order of the tests, both steam and electric, was as follows:

A train of six cars, including five standard passenger coaches loaned by the New York Central Railroad, and the dynamometer car, was started and run over a mile of track, acceleration being made as rapidly as possible with the power available. These same runs were repeated, dropping off one car at a time, until only the dynamo-meter car remained. Automatic records were kept of the draw-bar pull, speed, time, distance and the strength and direction of the wind. The condition of rail and the temperature were also noted. The same runs were repeated, using the two motor cars in place of the steam locomotive, the dynamometer car being used in some of the runs and a box car loaded to equal weight in subsequent runs. In

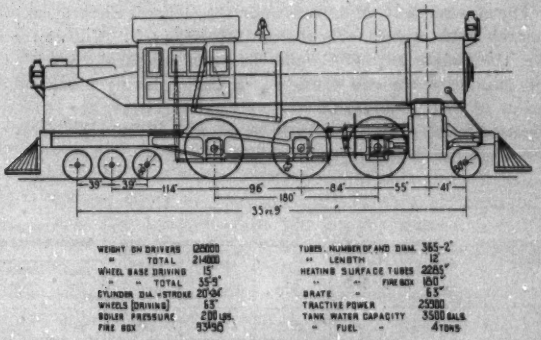

FIG. 2.—Outline of Steam Locomotive No. 1407.

the electric runs, additional records were kept of voltage, ampere and wattmeter readings. The watt-meter was not carried on the car, but was placed stationary at the point of feeding the third rail, thus avoiding any inaccuracy due to jarring. The voltage leads of the watt-meter were connected to the extreme end of the third rail and track, thus receiving at all times the exact voltage at the train, so that the energy delivered to the motor cars represented the net input and did not include losses in the feeder system.

The cars used in this test and the weights are given below:

New York Central locomotive	No.	4107	214,000 lbs.
General Electric motor car	No.	4	73,000 lbs.
General Electric motor car	No.	5	70,000 lbs.
Illinois Central dynamometer car	No.	17	45,640 lbs.
New York Central coach	No.	1885	48,200 lbs.
New York Central coach	No.	545	60,250 lbs.
New York Central coach	No.	1709	53,700 lbs.
New York Central coach	No.	508	51,450 lbs.
New York Central coach	No.	1798	54,600 lbs.

During the tests many runs were made, but for the illustration of this paper, representative and average runs only are given.

Electric Motor Cars No. 4 and 5.

The electric runs were made upon the General Electric experimental track against a head wind of 15 m.p.h. The rail was dry, the temperature 8° C., and the grade practically level. In the middle of the run there was a curve having a minimum radius of 875′, equivalent to about a 6½° curve, the friction effect of which may be assumed as approximately equivalent to one-tenth per cent. up grade of the steam runs.

No. of run.	Character of load.	Weight of load, tons	Total weight train, tons	Maximum speed.	Average speed.	Watt hours per ton mile.	
						From volt amperes.	From watt-meter.
1	6 Trailers.	157.	228.5	36.4	27.2	75.9	79.4
3	5 "	130.	201.5	37.9	28.6	78.4	82.0
5	4 "	104.	175.5	39.1	29.8	84.3	86.9
7	3 "	77.	148.5	41.0	30.6	84.7	93.4
9	2 "	47.	118.5	42.8	32.0	96.5	99.4
11	1 "	23.	94.5	44.7	33.1	115.0	114.0
13	No "		71.5	46.7	34.6	132.3	129.0

New York Central Steam Locomotive No. 1407.

All steam locomotive runs were made upon the New York Central main line track west of Schenectady, against an up grade of .1% and a head wind of 15 m.p.h. The temperature was 4° C. and the rail wet with a very light falling snow.

No. of run.	Character of load.	Weight of load, tons.	Total weight of train, tons	Maximum speed, m.p.h.	Average speed, m.p.h.
2	6 Trailers.	157.	264.	89.0	28.2
4	5 "	130.	237.	41.3	28.4
6	4 "	104.	211.	40.9	27.4
8	3 "	77.	184.	45.7	27.3
10	2 "	47.	154.	48.0	30.1
12	1 "	23	130.	50.9	33.0

Although this locomotive was especially built for suburban or acceleration work, and was provided with a large fire-box, giving it facilities for rapid steaming, the pressure dropped from 200 lbs. to less than 185 lbs., during the first part of acceleration. In starting, the throttle was opened wide and steam used full stroke, the engine being hooked up as acceleration proceeded. Curves showing detail of these runs are given in Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15.

While the electric runs had the advantage of dryer rails than the steam runs, the driving wheels were not slipped in either instance. Although the steam locomotive was able to give a maximum tractive effort at starting equal to that obtained electrically, this high tractive effort was not maintained, but immediately fell with increased speed, even with the most expert handling.

As the acceleration curves produced by the steam locomotive and electric motor cars have different shapes, and as in the two tests there was about the same weight upon the drivers, it is interesting to note how well this driver weight was utilized. This is shown by the following tables giving the speed reached in ten, twenty and thirty seconds with equal trailing load for both electric and steam trains.

MILES PER HOUR ATTAINED IN 10 SECONDS.

No. of trailers	1	2	3	4	5	6
Motor cars No. 4 and 5	23.5	20.7	17.3	14.4	12 6	11.2
Locomotive No. 1407	14.	13	12.5	12.	10.	9.7

MILES PER HOUR ATTAINED IN 20 SECONDS.

No. of trailers	1	2	3	4	5	6
Motor cars No. 4 and 5	34.	32.3	29.4	27.4	24.5	21.2
Locomotive No. 1407	25.	21.2	21.5	19.5	18	16.3

MILES PER HOUR ATTAINED IN 30 SECONDS.

No. of trailers	1	2	3	4	5	6
Motor cars No. 4 and 5	38.2	36.4	34.2	32.4	30.3	28.1
Locomotive No. 1407	31.7	30.2	27.2	24.7	23.2	20.8

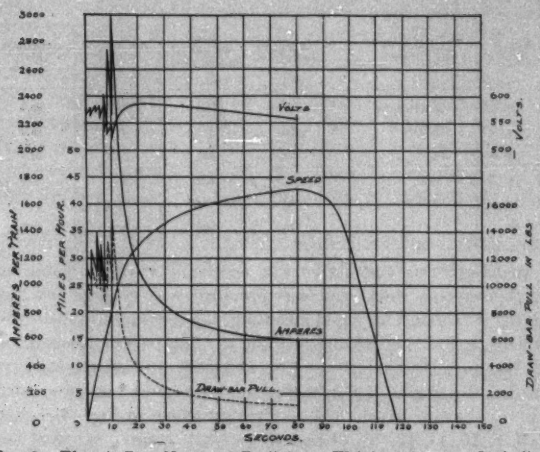

FIG. 3.—Electric Run No. 1. 6 Trail Cars—Weight 157 tons. Including Motor Cars 228.5 Tons. Power on 4170 ft. Distance Run 5380 ft. Watt hours per ton mile 79.4.

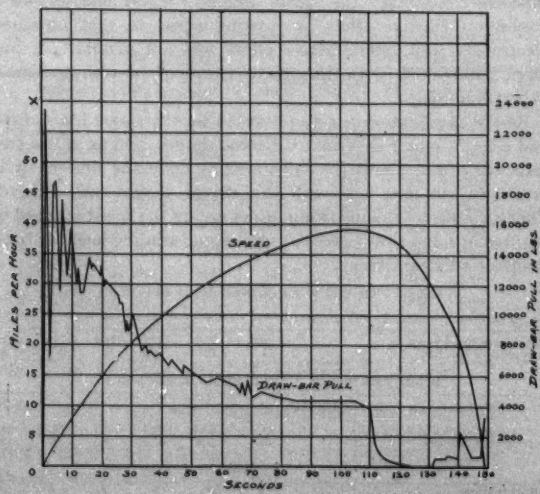

FIG. 4.—Steam Run No. 2. 6 Trail Cars—Weight 157 tons. Including Locomotive 264 tons. Power on 4035 ft. Distance Run 6150 ft.

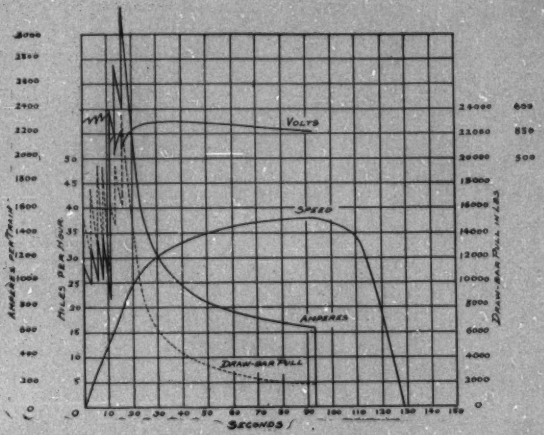

FIG. 5.—Electric Run No. 3. 5 Trail Cars—Weight 130 tons. Including Motor Cars 201.5 tons. Power on 4170 ft. Distance Run 5380 ft. Watt hours per ton mile 82.

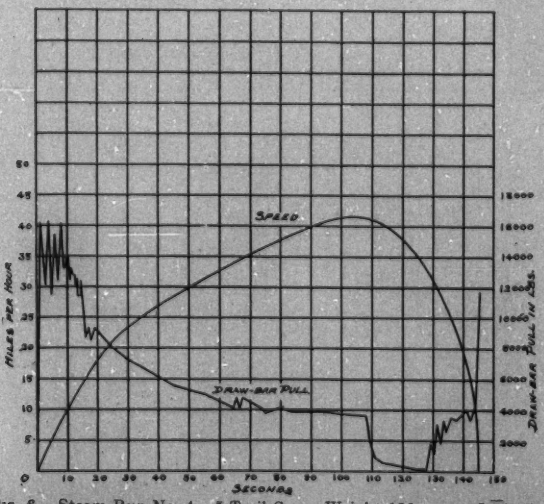

FIG. 6.—Steam Run No. 4. 5 Trail Cars—Weight 130 tons. Including Locomotive 237 tons. Power on 4270 ft. Distance Run 6050 ft.

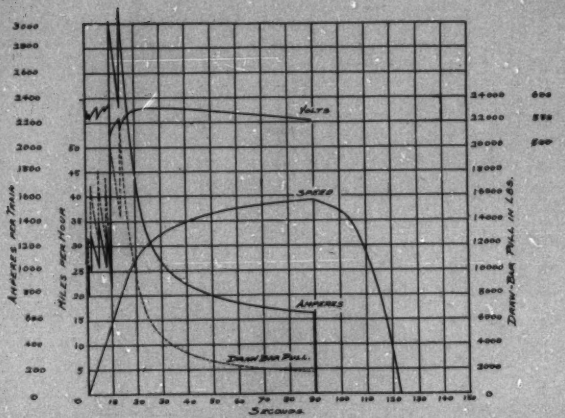

FIG. 7.—Electric Run No. 5. 4 Trail Cars—Weight 104 tons. Including Motor Cars 175.5 tons. Power on 4135 ft. Distance Run 5380 ft. Watt hours per ton mile 86.9

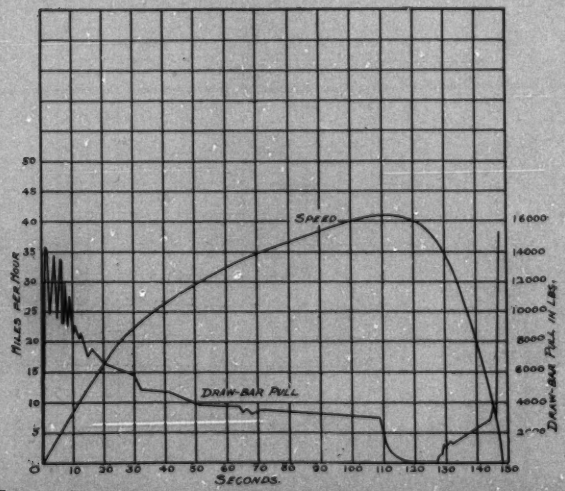

FIG. 8.—Steam Run No. 6. 4 Trail Cars—Weight 104 tons. Including Locomotive 211 tons. Power on 4490 ft. Distance Run 5943 ft.

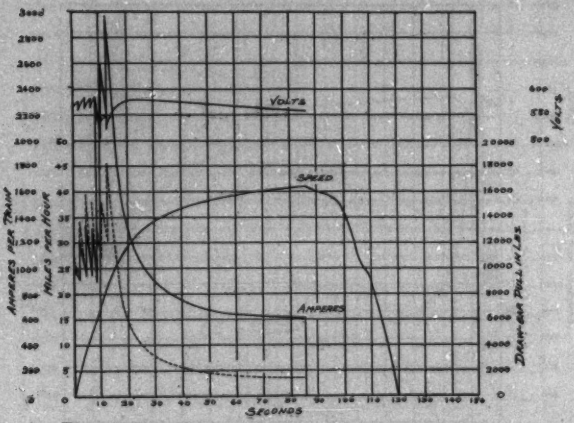

FIG. 9.—Electric Run No. 7. 3 Trail Cars—Weight 77 tons. Including Motor Cars 148.5 tons. Power on 1470 ft. Distance Run 5370 ft. Watt hours per ton mile 93.4.

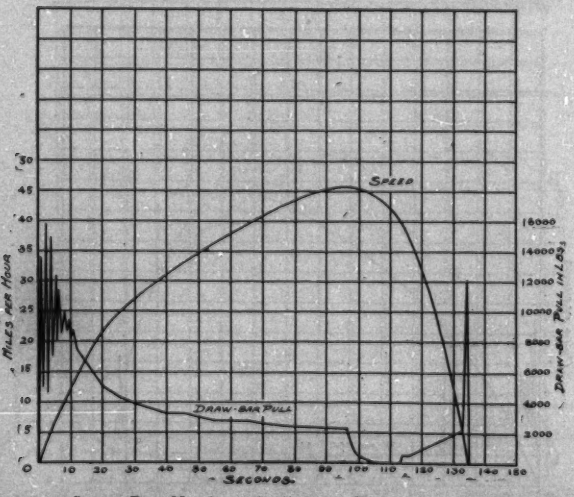

FIG. 10.—Steam Run No. 8. 3 Trail Cars—Weight 77 tons. Including Locomotive 184 tons. Power on 4520 ft. Distance Run 5980 ft.

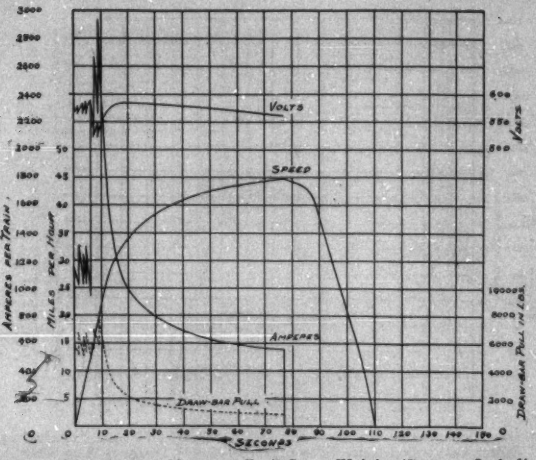

FIG. 11.—Electric Run No. 9. 2 Trail Cars—Weight 47 tons. Including Motor Cars 118.5 tons. Power on 4100 ft. Distance Run 5490 ft. Watt hours per ton mile 99.4.

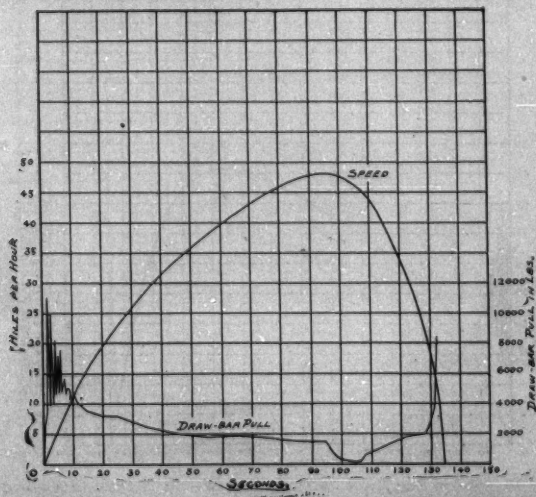

FIG. 12.—Steam Run No. 10. 2 Trail Cars—Weight 47 tons. Including Locomotive 154 tons. Power on 4455 ft. Distance Run 5927 ft.

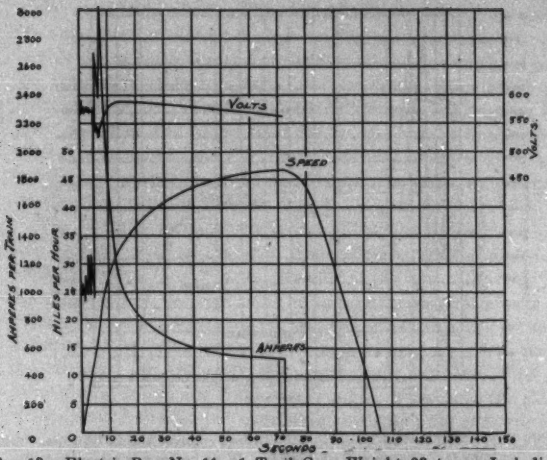

FIG. 13.—Electric Run No. 11. 1 Trail Car—Weight 28 tons. Including Motor Cars 94.5 tons. Power on 4060 ft. Distance Run 5850 ft. Watt hours per ton mile 114.

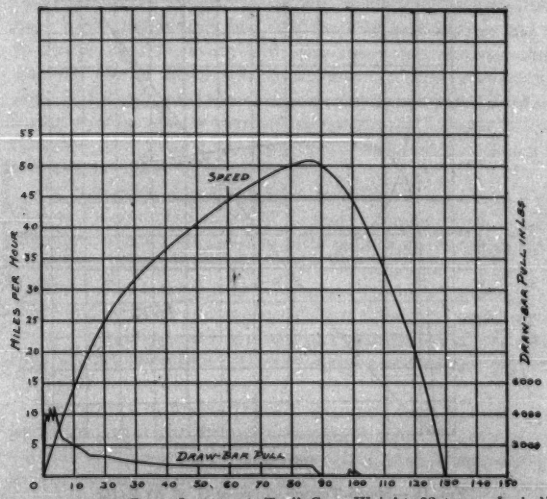

FIG. 14.—Steam Run No. 13. 1 Trail Car—Weight 28 tons. Including Locomotive 130 tons. Power on 4460 ft. Distance Run 6260 ft.

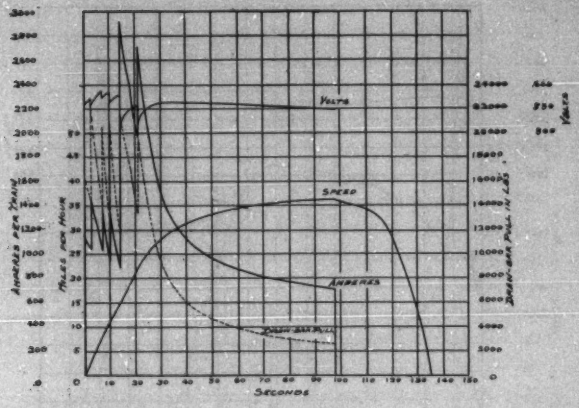

FIG. 15.—Electric Run No. 13. No Trailers. Motor Cars 71.5 tons. Power on 4089 ft. Distance Run 5360 ft. Watt hours per ton mile 129.

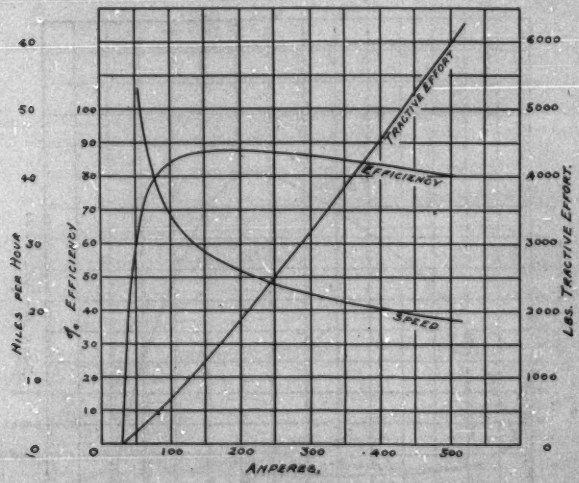

FIG. 16.—Speed-Torque Curve of G. E. 53 Motor.

An inspection of the above tables clearly brings out the fact that the electric motors during acceleration can more effectively utilize the weight upon their drivers than can a steam locomotive. As rapid acceleration is especially important when stops are a mile or so apart, the electric motor has an advantage in being able to cover the same distance in the same time with less energy expended and at less maximum speed than a steam locomotive, owing to its being able to maintain its maximum accelerating rate for a longer period.

The average speed given in both steam and electric tables is the average speed of the train while it is in motion, and does not include time of any stop at the end of the run. Starting from rest, the power was kept full on to the three-quarter mile post where the power was shut off and the brakes applied in such a manner as to bring the train to rest as near the mile post as practicable. In the tests the steam train ran from 5 to 15% over a mile before the train was brought to rest and the electric trains from 2 to 4%, but even with the longer distance the average speed of the steam runs only approached that attained in the electric runs made over a shorter distance. A comparison of the two sets of runs on the basis of average speed is, therefore, not quite fair to the electric motor car, as its average speed would have been considerably higher if the length of the run had been the same as that made with the steam locomotive. An inspection of the tables will show, however, that even with the shorter distance run, the electric motor cars were able to make higher average speeds than the steam locomotive over its longer distance, and these higher average speeds were obtained also with a lesser maximum speed.

The maximum speed of a train making a given run in a given time serves as an indication of its energy consumption. A train, therefore, which is so handled as to make a given run in a given time, with lowest maximum speed, will consume less energy for the run. The electric runs tabulated all show a lower maximum speed and a higher average speed than those runs made with the steam locomotive, and the energy consumption of the electric runs should, therefore, be less for the same service performed than with the steam locomotive.

The motors of an electrically equipped train may be placed upon the trucks of ordinary passenger coaches, each carrying its full complement of passengers, and thus lessen the gross weight by elimination of the locomotive. The true measure of

comparison between steam and electrically propelled trains should be the energy per seat mile rather than per ton mile, as

FIG. 17.—General Electric Railroad

the latter value is based upon the total train weight and includes a considerable proportion of dead weight embodied in loco-

FIG. 18.—Electric Motor Car, No. 4.

tive and tender. The steam locomotive not only adds to the train weight, the weight necessary to ensure traction, but is

further handicapped by additional weight on pony trucks and usually a tender.

FIG. 19.—General Electric Railroad Yard.

As an illustration, the following table has been prepared from these tests showing the number of cars in the train, the number

FIG. 20.—Train Used in Electric Tests.

of passengers carried (each car seating 64 persons) and the energy, which for convenience we have given in watt hours, required per passenger for both steam and electric runs.

NET ENERGY PER PASSENGER CARRIED.

Number of Cars.	Number of Passengers	Watt Hours per Passenger	
		Steam.	Electricity.
6	384	43.9	29.7
5	320	52.2	32.1
4	256	57.5	33.5
3	192	77.4	37.5
2	128	103.0	45.2
1	64	187.8	45.2

This table is based upon the actual net energy delivered to the wheels of the train and does not include the losses inherent to any system of operation. The results tabulated may, therefore, be considered as fundamental, and typical of the two systems of operation—the steam locomotive and the electric motor car.

The following table gives the efficiencies for the seven electric runs, the efficiency being the ratio between net energy output to the wheels and total volt ampere input:

EFFICIENCY OF ELECTRIC RUNS.

Trailers.	Average m. p. h.	Watt hours per ton mile.		Efficiency, of run.
		Output.	Input.	
6	27.2	59.1	79.8	74. %
5	28 6	61.0	82.0	74 3%
4	29.8	63.8	84.9	75.8%
3	30.6	68.0	90.2	75.8%
2	32.	69 6	99.6	69.9%
1	33.1	75.8	112.8	66.7%
0	34.6	79.8	130 0	61 5%

An accurate comparison of the relative efficiency or coal consumption of steam and electric power for similar service would require an extensive series of tests with indicator and dynamometer on the performance of the steam locomotive.

As a matter of interest we have secured an approximate comparison from a single test by weighing the coal and water taken by steam locomotive No. 1407 for a period of 24 hours, covering four trips between North White Plains and Grand Central Station, a distance of 24.75 miles, on the Harlem Division of the New York Central Railroad. The trips occupied about 4 hours, the yard movements about 1 hour, and the locomotive was idle for 19 hours.

Following is a detailed record of the service covering the 24 hours:

NORTH WHITE PLAINS TO GRAND CENTRAL STATION.

Time.	Number of Cars.	Number of Stops.	Total Weight.	Weight of Cars.	Effective h. p. h.
83.5 min	8	21	204 tons	97 tons	129
Lay-over.....6 hours.					

GRAND CENTRAL STATION TO NORTH WHITE PLAINS.

Time.	Number of Cars.	Number of Stops.	Total Weight.	Weight of Cars.	Effective h. p. h.
66.25 min.	5	17	278 tons	171 tons	255
Lay-over.....		12 hours.			

NORTH WHITE PLAINS TO GRAND CENTRAL STATION.

Time.	Number of Cars.	Number of Stops.	Total Weight.	Weight of Cars.	Effective h. p. h.
60.3 min.	7	18	387 tons	280 tons	231
Lay-over.....		¼ hour.			

GRAND CENTRAL STATION TO NORTH WHITE PLAINS.

Time.	Number of Cars.	Number of Stops.	Total Weight.	Weight of Cars.	Effective h. p. h.
59.75 min.	4	20	256 tons	149 tons	246
Lay-over.....		1¼ hours.			

Total effective h.p. hours, hauling coaches 861
Coal consumed .....13,412 lbs
Coal per effective h.p. hour .....15.6 "

The effective h.p.h. given above is the energy required for movement of the cars only, exclusive of the locomotive; and was determined from the draw-bar pull taken by dynamometer car in previous tests over the same route.

The coal consumption covers all coal burned during the period of 24 hours, not only for movement of cars, but also movement in the yard and the banking of fires during lay-overs.

The effective h.p.h. to move the cars serves as the basis of comparison with electric service, the coal consumed by the locomotive for whatever purpose being properly chargeable to the net work done by the locomotive during the period.

The efficiency of an electrical system, as an average under variable load, may reasonably be assumed as follows:

Engine	90%	Efficiency
Alternator	92%	"
High Potential Transmission	98%	"
Transformers	97%	"
Converters	92%	"
Third Rail	95%	"
Motors, including control	75%	" 51.33%

This percentage of effective horse-power output of motors to i.h.p. of engine will vary somewhat, depending on the load

factor. As an even figure we will assume an efficiency of 50%.

Coal consumption per indicated h.p.h. from actual records of electric power stations, is in some cases less than 2 lbs., the average being about 2½ lbs. At the latter figure, the coal per effective h.p.h. output of electric motors would be 5 lbs. Assuming the head end air resistance as 10% and as the electrical equipment would increase the weight of the cars about 20%, the actual comparison of coal consumption would be approximately in the ratio of 6.6 for electric and 15.6 for steam.

Assuming that coal for a power station may be purchased for 80 per cent. of the cost per ton of that used in the locomotives, and that the cost of coal for electrical power is about one-third of the total cost, including maintenance and interest on investment, it is probable that the actual gross cost of electrical power would closely approximate the coal consumption of a steam locomotive in this class of service, the maintenance of the electrical equipment and attendance required being, however, considerably in favor of the electric power.

We wish to express our thanks to Mr. E. C. Schmidt, Professor of Railway and Mechanical Engineering, University of Illinois, for his able management of the dynamometer car, assisted by Messrs. J. J. Snodgrass and R. W. Lohmann; also to Messrs. A. H. Armstrong and E. F. Gould of the General Electric Company for their careful supervision and calculations of the electric tests.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 19th, 1902

AN EXPERIMENT WITH SINGLE-PHASE ALTERNATORS ON POLYPHASE CIRCUITS.

BY C. O. MAILLOUX.

An experiment of considerable theoretical and practical interest, incidentally illustrating the elasticity of the polyphase current system, was recently tried successfully at Phœnix, Arizona. This experiment was a practical demonstration of the possibility of using single-phase alternators as the source of energy for supplying polyphase currents, both two-phase and three-phase, and also for supplying direct current to a transmission and distribution system. The experiment was conducted at Phœnix on April 7, 1902, by the writer, assisted by Mr. D. W. Beldon, the electrical engineer of the Phœnix Light and Fuel Company, of Phœnix, using the machinery and facilities of the old steam station and of the new transformer sub-station of that company. A summary description of the plant will be useful in explaining the conditions of operation and the circumstances leading to and attending the experiments made.

About three years ago the Phœnix Light and Fuel Company entered into negotiations with the Arizona Water Company, which controls the irrigation canals and the water used for irrigation in the Phœnix Valley, or that portion thereof lying north of the Salt River, for the exclusive privilege of utilizing for water power purposes all water controlled by the Arizona Water Company. In the summer of 1899 a commission of engineers, including the writer, selected sites for two water power stations, the locations being fixed at such points that the

water could be utilized for power purposes without detriment to its subsequent use for irrigation.

The designs for the two power stations and for a receiving or transformer station, were completed by the writer, and contracts were made about a year ago. The first station was completed and put in operation in April, 1902. This station is situated on an Indian reservation about 24 miles east of Phœnix. It comprises two generator units, each of 200 kilowatt capacity, each belted to a separate turbine.

Station No. 2, now in process of construction, is located at the Arizona Falls, at a point about nine miles north-east of Phœnix. This station is expected to be completed about August 1st. The design of this station is substantially the same as that of station No. 1, but the two generator units have only half the capacity, 100 kilowatts. The aggregate normal capacity of both stations will be 600 kilowatts. The turbine capacity is 1.75 h.p. per kilowatt, or 1,050 aggregate h.p.

The transformer sub-station is located in a new building on the same plot of ground as the old steam plant of the company, but at a distance of about 300 feet from it. This station is the receiving point for the electrical energy to be generated at the two power stations. The transmission line (three wires, copper, No. 6 B. and S.) runs from Station No. 1 past Station No. 2 where it makes a loop connection. The two stations are to be operated in parallel.

The system uses three-phase transmission, delivering energy at about 22,500 volts at the transformer station, where there are two sets of lowering transformers, including those for lighting current service, which are of the Scott three-phase, two-phase, type, stepping down from three-phase, 22,500 volts, to two-phase, 2,250 volts; and those for the power current service, of the ordinary type, stepping down to three-phase, 350 volts, for supplying the rotary converters, of which there will be two, each 150 k.w. The frequency used is 60 cycles per second.

The company purposes to furnish A. C. current for both lighting and power from the two-phase, 2,200 volts, feeder lines, and also current for power purposes only, at 500-550 volts, D. C., for operating street railway motors, elevators and for supplying power for various large and small customers. The power current system is to be supplemented by a storage battery having a capacity of about 300 k.w. hours.

The old steam generating plant, which is to be discarded

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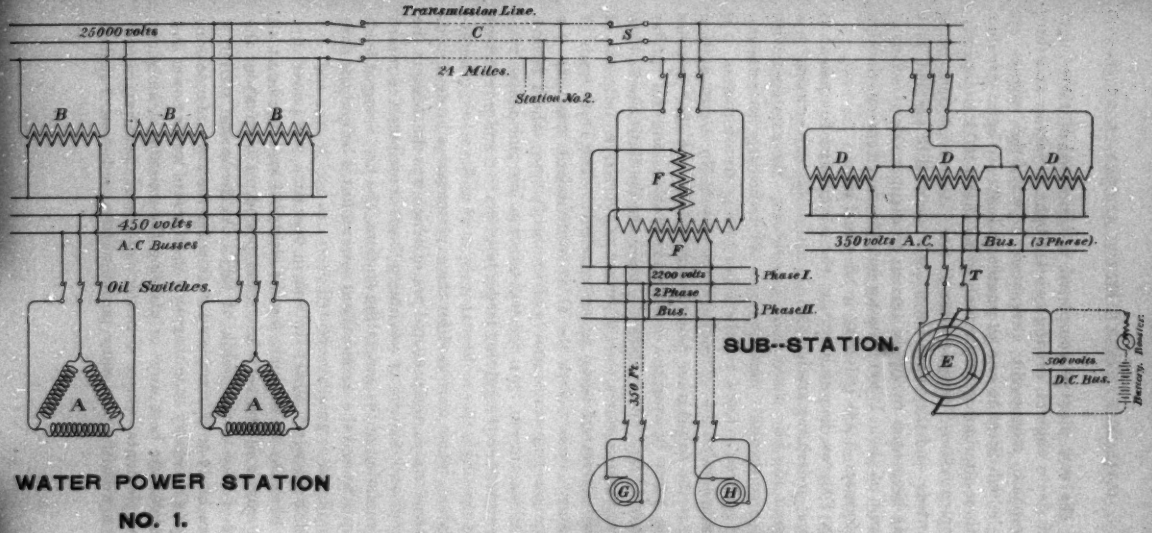
Transmission Line.
25000 volts
C
S
24 Miles.
Station No. 2.
B
B
B
450 volts
A.C Busses
Oil Switches.
A
A
F
F
2200 volts
2 Phase
Bus.
Phase I.
Phase II.
350 F.
D
D
D
350 volts A.C.
Bus. (3 Phase).
T
E
300 volts
D.C. Bus.
Battery. Booster.
SUB--STATION.
G
H
WATER POWER STATION
NO. 1.
STEAM STATION.

FIG. 1.

after the new plant is completed, is composed of three high-speed steam engines, driving two arc light dynamos, and three single-phase monocyclic alternators. Two of the engines are each belted direct to one alternator and one arc light dynamo. The three alternators, respectively of 50, 75 and 100 k.w. capacity, are operated as "single-phasers," the "teaser" circuit being discarded; and they have never been operated in parallel, each having been used to supply current to distinct sets of feeders at an e.m.f. of about 2,200 volts for incandescent lighting, through transformers, 2,200–104 volts, in the usual way.

Fig. 1 shows diagrammatically the system and equipment at the first generating station (No. 1) and at the sub-station. A A represent the two three-phase generators; the exciters, with their circuits and connection and all indicating instruments, being omitted. B B B are the three raising transformers. C is the transmission line extending from station No. 1 past station No. 2 to the sub-station, being controlled by the line switches at the point of entrance in the sub-station, and by similar switches at each power station. D D D are the three three-phase lowering transformers for the rotary converters E (only one of the two converters being as yet installed). The D. C. leads of the rotary connect with the D. C. switchboard bus-bars. F F are the lowering transformers of the Scott type, which receive three-phase current from the transmission line and deliver two-phase current to the lighting feeder bus-bars. G and H represent two of the single-phase alternators located in the steam generating station, which were used for the experiments to be described.

Various causes, the principal one of which was the delay in the shipment and delivery of machinery, have contributed to retard the completion of the generating stations, the first being at least four months and the second about seven months behind the date of completion originally expected.

With both water power stations in operation, the power supply is likely to be adequate for the electrical load carried at all times, except in the very low water period, or from about the middle of May to the middle of July. As the second station is not now likely to be completed in time for the low water season, it became necessary to anticipate a shortness of water power and to consider the best ways of utilizing the existing steam plant as a supplemental source of power capable of operating in conjunction with the first water power station, and even of replac-

ing it altogether. and of alone carrying the load wholly or in part, if necessary, in case of emergency.

The high cost and low quality of fuel here, of course, make it desirable to reduce the hours of operation of the steam station to the lowest number possible. With this object in view, arrangements have been made to carry the entire incandescent lighting load from the sub-station whenever possible. It is the intention, as soon as the necessary apparatus can be procured, to replace the present arc lights, series direct current open arc system, with the alternating current enclosed arc system. For the present the arc light circuits are to be fed from the existing arc light dynamos, driven either by the present steam engines, when water power is insufficient, or else by motors taking electric power from the sub-station, when the water power is ample, the motors being so placed that the change in driving power for the dynamos may be quickly made by merely changing the belts from the engine to the motor pulley.

There were two problems to be considered: First, the problem of running the incandescent lights partly or wholly from the steam-driven, single-phase alternators; second, the problem of generating direct current for the power circuit and for charging the battery so as to use it for peaking the load, and also for using it in emergencies, the battery being especially useful when the power available is at the lowest point. The expedient of transferring some of the lighting feeders from the two-phase bus-bars in the transformer station to one or more of the three single-phase alternators in the steam station, was resorted to provisionally, but it involved too much complication in switches and manipulation to be desirable or trustworthy as a permanent feature. Arrangements were therefore made for coupling the single-phase alternators, each with one phase of the two-phase bus-bars in the sub-station. The necessary connections having been made, and a Lincoln synchronizer having been procured and connected, the experiment of coupling first one, then another of the alternators in multiple with either of the two phases was tried, the alternator being brought to the synchronous speed by regulating the engine throttle-valve. The next step was to connect one of the alternators with each phase. This was easily done. There was no difficulty in making the alternators keep in step, and in making them carry a proportion of the total load. It was also found, as was to be expected, that the alternators

could be utilized in balancing the two phases, in case they were unequal in potential difference, owing to unequal loads.

The first problem, therefore, being solved by these experiments, the second problem was then taken into consideration. A little thought showed that the rotary converter, if kept running by the electric current from a storage battery, could be used and could be depended upon, being a three-phaser, on the A. C. side, to maintain, first, a three-phase current relation on the transmission line, by working back through its transformers, and second, a two-phase relation on the feeder bus-bars by current working back through the Scott three-phase-two-phase transformers. It was also evident that any source of three-phase current supply would keep the rotary converter running and do the same thing, but the interesting question was, could the rotary converter be used without such source of extraneous current to keep it running, and could it then maintain the desired phase relations? In other words, could two single-phase alternators be maintained in two-phase relation by means of a rotary converter, when they were the sole source of the energy conveyed to the entire system. After careful consideration of all the reactions involved, the writer came to the conclusion that this could be done, and the experiment was decided upon. The results completely justified the confidence with which the experiment was tried. The diagram (Fig. 1) shows the conditions attending the experiment.

The generators A A having been connected with the transformers and excited so as to give the full line voltage on the transmission line C, the rotary converter E was then started in the regular way. This having been done, two of the single-phase alternators were coupled in succession to the feeder bus-bars, one to each phase. In coupling each alternator, a Lincoln synchronizer, suitably connected (not shown in the diagram), was used as a phase indicating device. After the two alternators had been coupled, each to one phase, the connections of the Lincoln synchronizer were changed so as to show the relation between the two phases of the lighting feeder bus-bars. The instrument showed that a perfect quarter-phase relation was being maintained between the two phases, as was expected. The load on each machine could be adjusted, both by regulating the steam supplied to the engine at the throttle-valve, and by changing the excitation of the magnetic field.

After all adjustments had been completed, the line switches

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s were then quickly pulled open, thereby disconnecting the transmission line, and shutting off all electric energy supplied from the water power station. At the instant of disconnecting, the speed of the rotary converter fell off slightly, as was evident not only by the frequency pitch or tone, but also by the readings of the D. C. and A. C. voltmeters. This falling off was ascribed to the fact that the engine throttle-valves were not fully open. On opening the throttle, the speed rose gradually, until the frequency again became about the same as it was before disconnecting the transmission line. The index of the Lincoln synchronizer remained all the time at a point 90° from the position of synchronism, showing that the two single-phase alternators were being kept as perfectly in the same two-phase relation as when the rotary converter was run with current supplied from the transmission line. The external load was then varied by opening and closing the feeder line switches at the lighting switchboard. The maximum load put on was equivalent to more than three-quarters of the full current capacity of each alternator; the load being composed almost entirely of incandescent lights; the power factor was, of course, somewhat high.

After continuing the experiment for about ten minutes, the A, C. switches, T, of the rotary converter were opened. Mr. Beldon, who was in charge of the apparatus at the steam generating station, thereupon immediately disconnected the alternators from the feeder bus-bar lines, the synchronizer having shown that the quarter-phase relation was lost at the same instant that the rotary converter was disconnected. The experiment was repeated with slight variations two or three times, and each time with perfect success. It was found that by opening the engine throttles somewhat more than was done in the first experiment, and increasing the steam pressure available at the engine cylinder before disconnecting the transmission line, there was less falling off of the frequency at the instant of disconnecting. It was observed that the A. C. current in the rotary converter increased slightly, as was to be expected at the time of disconnecting the transmission line. This was, of course, due to the new inter-reactions taking place between the single-phase alternators and the rotary converter in consequence of the new function imposed upon the converter, that of acting as an electromagnetic coupling and fly-wheel for the two single-phase alternators. It was found that the amount of this current could be varied, to some extent, as was to be expected, by varying the

field strength of the rotary converter. There were no facilities for imposing a D. C. current load on the rotary converter in addition to the load resulting from its operation as a phasing device for the two alternators. There is no reason to doubt, however, that a D. C. current load could have been placed upon the rotary converter up to the full generating capacity of the two single-phase alternators serving as the source of current supply in the experiment.

The experiment may, therefore, be taken to be a sufficient demonstration of the possibility of using single-phase alternators to produce two-phase current, three-phase current and direct current, with an arrangement and under conditions such as are shown in the diagram.

The reactions which take place between the rotary converter and the single-phase alternators, through the intermediary agency of the two sets of transformers, are quite difficult to follow and to analyze, but the writer believes that the principle on which these reactions depend is really not difficult to grasp. After the transmission line is disconnected, the entire supply of energy appearing in the system, including that necessary to drive the rotary converter must, of course, come from the two single-phase alternators, because the two steam engines driving them are now the only prime movers. The correcting force which keeps the two single-phase alternators in the two-phase relation must, therefore, be produced by a transfer of energy between the rotary converter and the alternators. It may be that what actually takes place is a transfer of energy between the two alternators themselves, or between the two A. C. phases to which they are connected, or to put it differently, the two alternators maintain their phase relation by a transfer of energy from one phase to the other through the rotary converter acting as an electro-magnetic elastic coupling.

In order to simplify the reasoning, we may assume that the rotary converter is also of the two-phase type, and that both sets of transformers, B B B and F F in the diagram, are modified accordingly. If the rotary converter were of the two-phase type, then we might consider each of the A. C. phases as a single-phase synchronous motor connected with a single-phase alternator. The rotary converter would, of course, when once started, keep in step with the alternator furnishing it with current. If, now, we were to connect another single-phase alternator on the other A. C. phase, the effect would be that any

variation in the speed of one alternator would immediately react upon the other, through a sort of fly-wheel action of the rotary converter. The particular alternator whose frequency is increasing, owing to rise of speed, would have its load increased by an amount corresponding to the extra energy sent through the corresponding phase to the rotary converter. This energy would cause the rotary converter to accelerate. The moment the rotary begins to accelerate, it would literally " unload " the other phase, that is to say, the alternator on the other phase would have its load reduced by reason of its phase-lag behind the rotary converter. If the lag were sufficiently great, not only would the load be reduced to zero, but a " motor " current impulse would be sent from that phase of the rotary converter to the corresponding alternator, causing it to "speed up" and regain synchronism.

The synchronizing force, it is seen, comes from the phase connected with the leading alternator, to the phase connected with the lagging one. This, the writer believes, is the key to the explanation. In this particular case, there is a complication by reason of the fact that the rotary converter had three phases on the A. C. side, while the alternators were only two in number and were connected to a two-phase current system. But it will be readily seen from the diagram that there was a transmutation of phases by means of the two sets of transformers D D D and F F, through which the transfer of energy was made between the single-phase alternators and the rotary converter. The effect was substantially the same as if a two-phase rotary converter had been used. The only difference is that any disturbance in the frequency or any lead or lag in one A. C. phase, occasions cross currents which react on two of the phases on the A. C. side of the rotary converter, instead of one; and, reciprocally, any correcting current sent from the rotary converter to one of the alternators, either to increase its speed or to check it, will be sent partly over two phases instead of one.

The rotary converter, it is seen, is the coupling medium between the two alternators. It is in one sense an elastic coupling, since its operation depends on the cross currents due to slight differences of phase between the alternators and the corresponding A. C. phase of the rotary converter. It does, therefore, permit some variation in phase relation, just as would an elastic coupling. The elasticity of the coupling depends upon the amount of lag which must occur in order to cause the cross

currents necessary to correct and remove this lag and restore phase synchronism between the alternator and the corresponding phase of the rotary converter. The extent to which this lag or lead will occur, that is to say, the amount of de-phasing taking place between the A. C. phase of the rotary converter and the alternator connected with the said phase, will probably vary considerably in individual cases, according to the conditions. It is not unlikely that the frequency may have considerable influence on this amount, because the frequency determines the number of times per second that the correcting influence of the alternator can be exerted. The frequency being 60 cycles, the rotary converter can, by means of cross currents, exert a correcting influence sixty times per second on each phase, and, consequently, on each alternator, and the engine driving the same. Now, the engine itself can change its mean speed, r.p.m., only by varying the amount or the pressure of the steam which it admits into the cylinder at each half stroke. In this case the engines used were of the high-speed type, running somewhere between 230 and 260 r.p.m., one having a somewhat higher speed than the other. Assuming a speed of say 240 r.p.m., we have twice that number of steam admissions, or, say, 480 per minute, which is equivalent to 8 per second. With an engine speed of 300 r.p.m., for instance, there would be ten steam admissions per second. Even supposing each steam admission to be such, by reason of change of cut-off or steam pressure, that the engine speed would tend to vary so as to change the frequency of the alternator driven by the engine, there would be only eight such disturbing reactions per second, whereas with the frequency of 60 cycles used, there could be, as already seen, 60 speed-correcting reactions per second, or seven and a half times as many. Practically, the steam admissions do not all tend to change the frequency, so as to throw out of phase the alternator driven by the engine. In most engines there is a very slight "hunting" action, whereby the steam cut-off varies slightly, first above, then below, the precise point which would maintain the speed absolutely constant. This is due to the fact that the engine governor usually varies the cut-off too much when it operates, first making it too long, then too short. The correcting effect of the cross currents is such as to restrict this oscillation within narrow limits, and to increase the number of admissions which are just right, or so nearly so as to cause but little reaction. Of course in each case the disturbing effect, due to the variations

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in steam admission is increased and complicated by the disturbing effects inherent in the engine, namely, the variations in angular velocity due to inertia of reciprocating parts, and to variations in the pressure applied to the crank-pin at different parts of the revolution. These, however, are of the same relative periodicity as the steam admissions, and, like them, they cause slight fluctuations above and below the mean speed. These fluctuations become minimized by the fly-wheel action of the rotary converters, for when they represent a slight increase in angular velocity, they cause reaction, which tends either to increase the speed of the rotary converter, or to lighten its load, or both; whereas, when they represent a decrease in angular velocity, they have the contrary effect. These reactions are explained exactly as before by the circumstance that each alternator bears a relation to the rotary converter which is exactly the same as if a single-phase alternator were connected with a single-phase synchronous motor. The alternator itself may become a synchronous motor in case, for any reason, its phase should lag behind that of the synchronous motor, or, in this case, the rotary converter. When the number of correcting impulses per second is great in comparison with the number of disturbing impulses, one would naturally expect that the range of lag or the amount of de-phasing would be smaller. This question could only be determined definitely by comparative experiments made on circuits of high and of low frequency, and by making careful quantitative measurements in each case.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 19th, 1902.

METHOD OF ASCERTAINING BY MEANS OF A DYNAMOMETER CAR THE POWER REQUIRED TO OPERATE THE TRAINS OF THE NEW YORK CENTRAL & HUDSON RIVER RAILROAD BETWEEN MOTT HAVEN JUNCTION AND GRAND CENTRAL STATION, AND THE RELATIVE COST OF OPERATION BY STEAM AND ELECTRICITY.

BY BION J. ARNOLD.

In August, 1901, the writer was commissioned by the New York Central Railroad Company to study the conditions governing the operation of its trains between Mott Haven Junction and Grand Central Station, and to report upon the feasibility of operating them by electricity. This division consists of 5.3 miles of four-track road forming the trunk line, or main artery over which the trains from the three divisions of the New York Central and the main line of the New York, New Haven & Hartford Railroad enter the city of New York. For 2.58 miles from Mott Haven Junction the tracks are carried on an elevated stone and steel structure; then for 2.04 miles through a tunnel underneath the street, emerging into an open cut .68 of a mile long, then terminating at the Grand Central Station in an intricate stub-end yard, having about eight miles of switching tracks. Fig. 1 shows the map of this yard. Over this division are made nearly 600 train movements per day, as nearly all trains entering the yard or station must be returned to Mott Haven Junction, owing to lack of sufficient storage tracks at the Grand Central terminus.

The annoyance to passengers due to the use of steam locc-

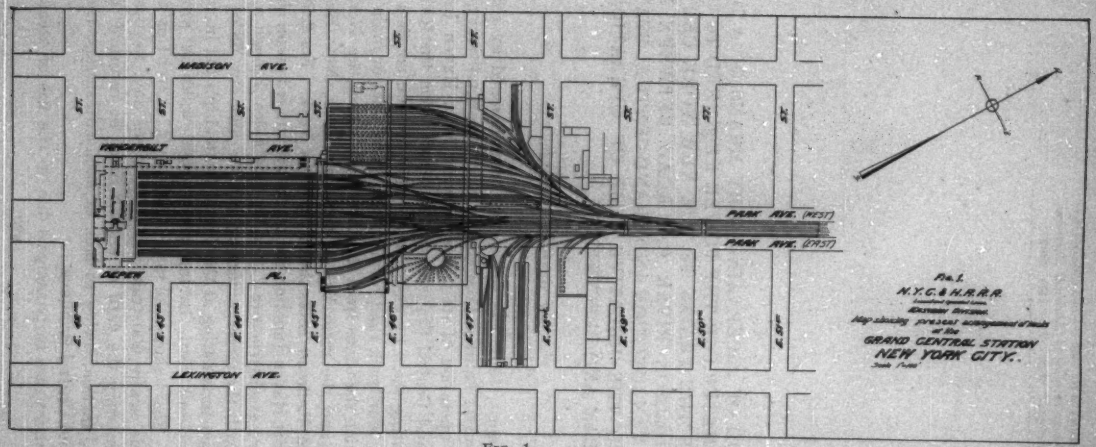

FIG. 1.

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motives in the tunnel, caused the company to examine into the advisability of adopting electricity, and it is through the courtesy of Mr. W. J. Wilgus, chief engineer of the company under whose directions the investigation was made, that the writer is allowed to present to this INSTITUTE the technical substance of this report.

All money values relating to total cost of installation, real estate, etc., and many other elements upon which the final recommendations of the report were based, together with many of the general recommendations and conclusions themselves, are necessarily omitted from this paper, but it is believed that the data given is sufficiently complete to enable one to check the technical conclusions herein given.

Soon after taking up the work it became evident, on account of the number and weights of the trains to be handled and the numerous variable elements entering into the operating system which would not adapt themselves conveniently to formulæ, that the most practical and satisfactory way of ascertaining the power required to propel the trains was to measure, by means of a dynamometer car, the draw-bar pull of a sufficient number of trains of various weights, to determine the average power required per train and from this compute the general load diagram.

A dynamometer car known as "Test Car No. 17," owned jointly by the Illinois Central Railway Company and the University of Illinois, was secured, and men thoroughly skilled in its use were employed to operate it. This car was coupled between the engine and the train in each case, and operated on trains running over the different divisions of the road, so that not less than four runs, two or more in each direction, were made for each class of train. Since the trains of all divisions, including those of the New York, New Haven & Hartford Railroad, run over the New York Central tracks between Mott Haven Junction and Grand Central Station, the records of the New York Central trains for this division will apply to trains of equal weights on the New York, New Haven & Hartford road, and were so considered in the calculations.

Description of Dynamometer Car:—In the dynamometer car employed, which is shown in Figs. 2 to 6 inclusive, the draw-bar is secured by means of a suitable rod to a piston head which fits closely in a cylinder filled with oil. The pull at the draw-bar thereby produces a pressure upon this oil which is transmitted

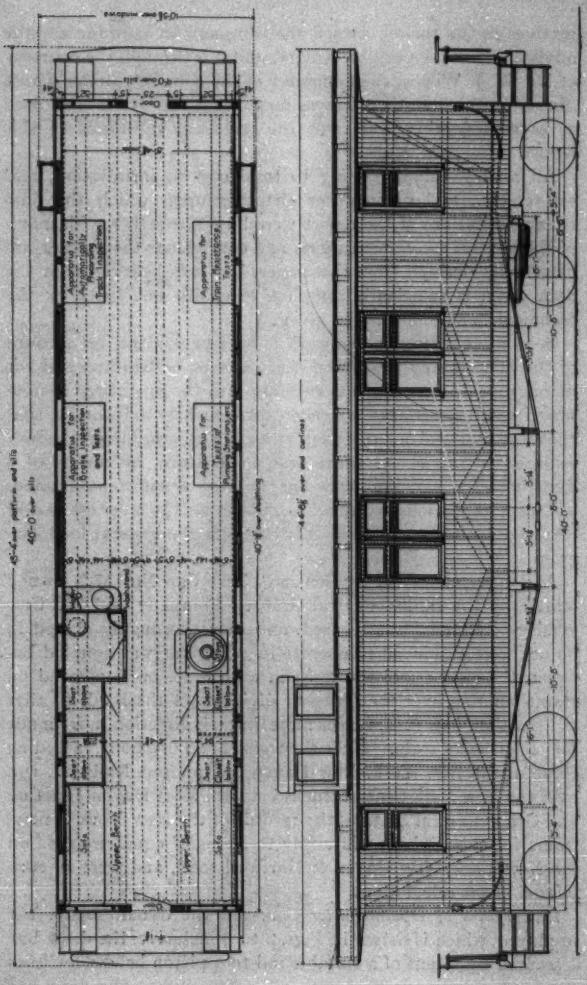


FIG. 2.

Railway Test Car of the Illinois Central R. R., and the Mechanical Engineering Department of the University of Illinois.

FIG. 3
Exterior of Dynamometer Car.

FIG. 4
Interior of Dynamometer Car.

FIG. 5
Working Table and Recording Devices of Dynamometer Car

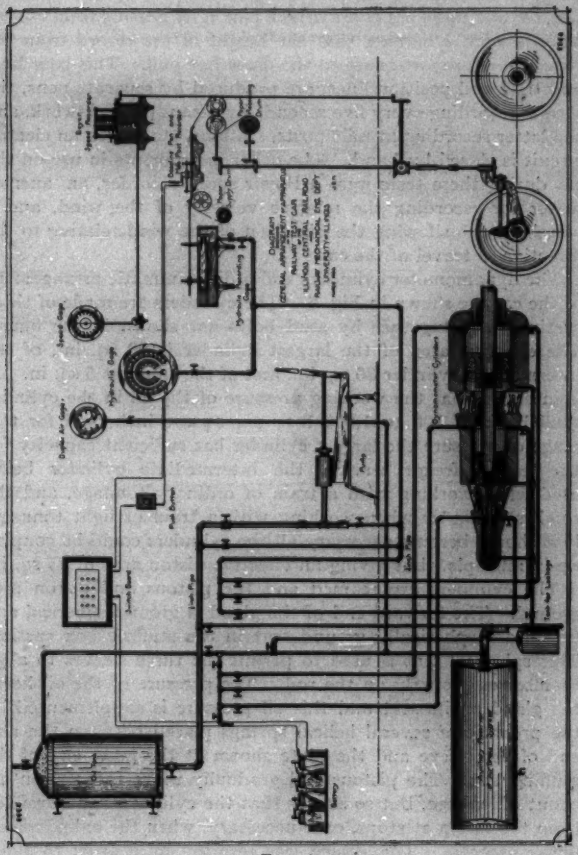


FIG. 6

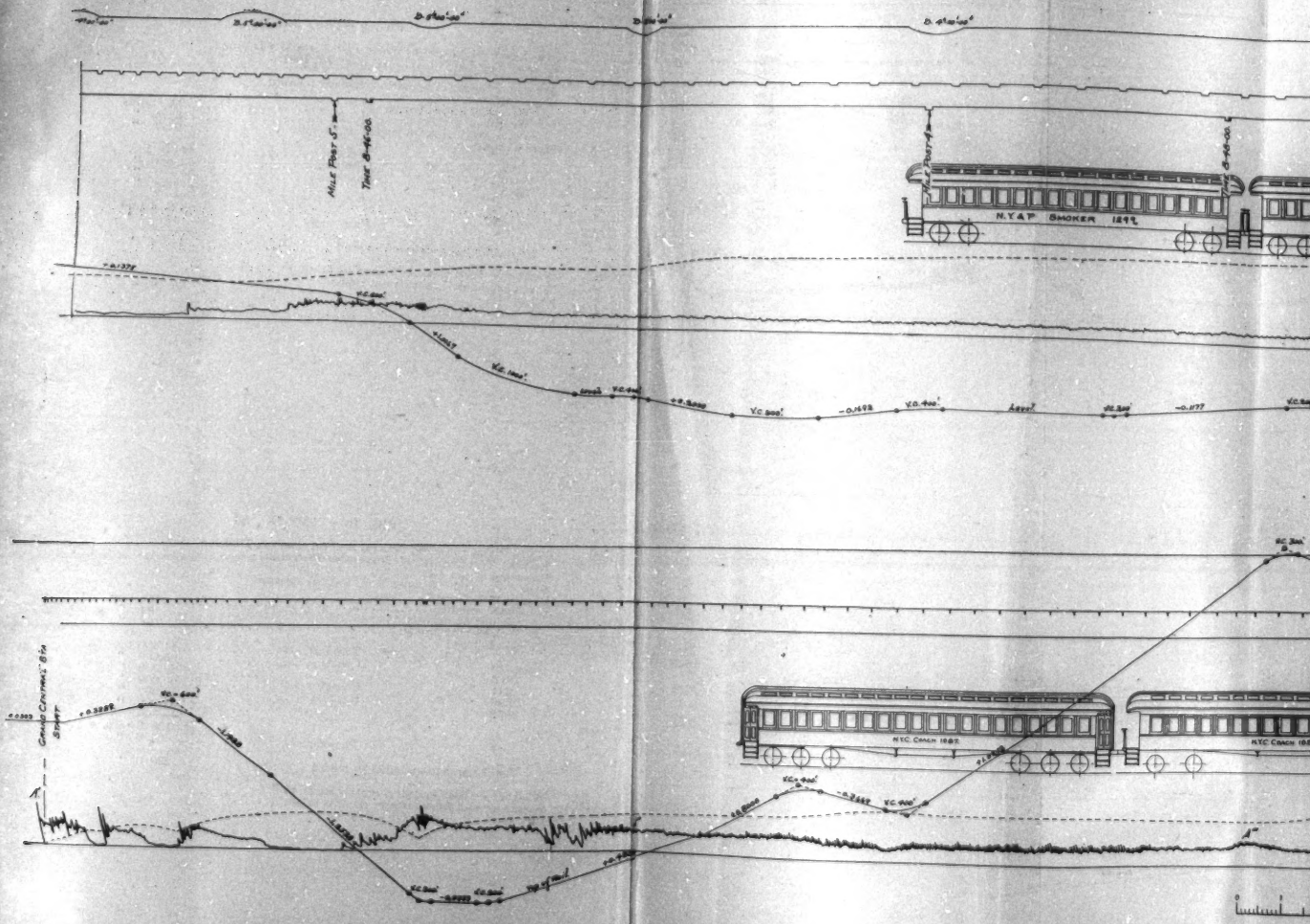
Diagrammatic Arrangement of Dynamometer Car.

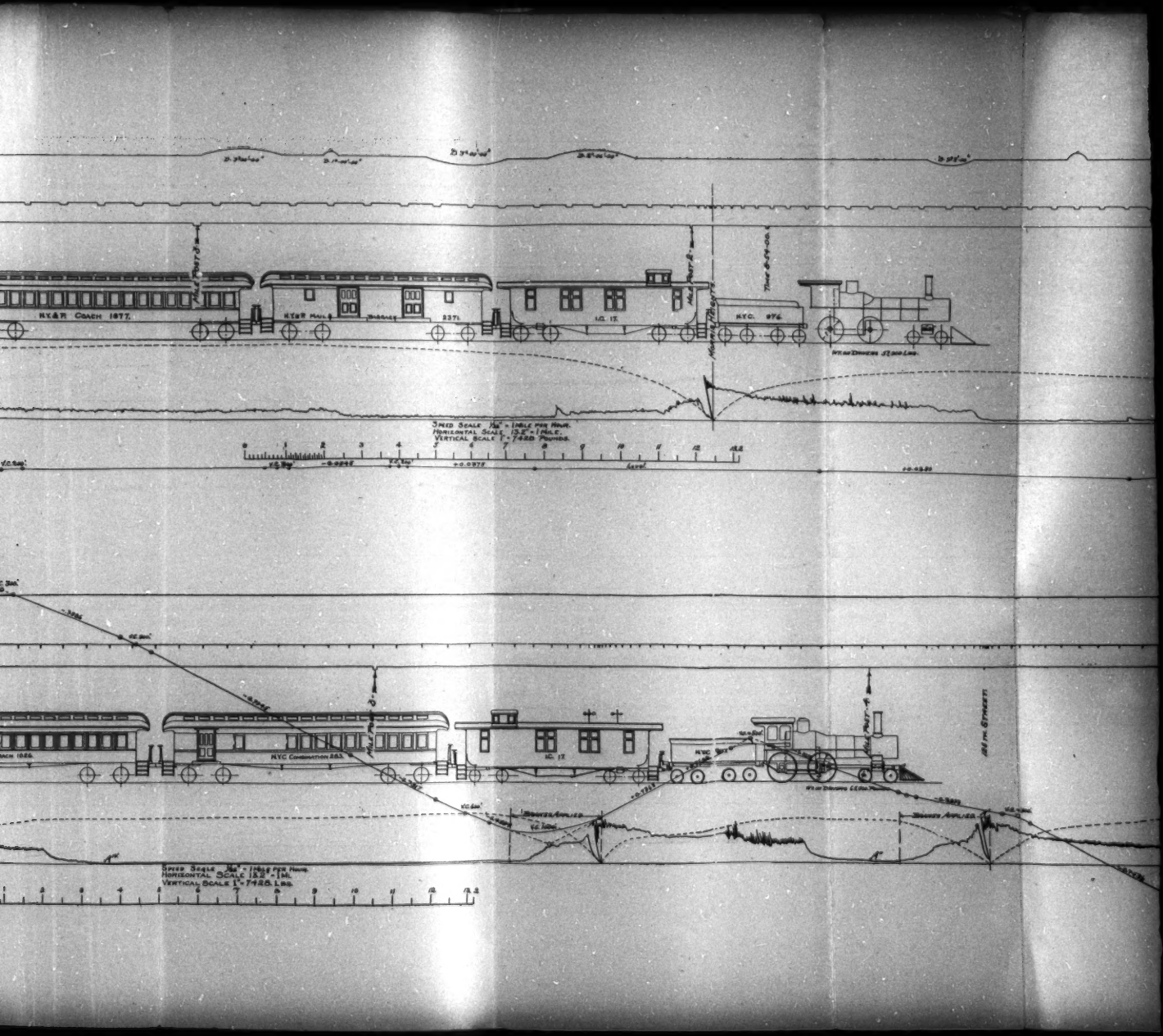
through suitable piping to the recording device, consisting essentially of a Bourdon gauge, which by means of a suitable arm and pen records upon paper are driven past it by gearing from the car axle, in such a manner that the height of the record from the base line is proportionate to the draw-bar pull. This base line, and time and position lines, are produced by separate pens, the former recording every five seconds by means of clock-work, and the latter recording at mile posts, stations, etc., when an electric circuit is closed by hand. The other instruments in use on the car during these tests were a Boyer speed recorder, an anemometer for recording the relative velocity of the wind, and a weather vane showing the direction of the wind relative to the direction of travel of the car.

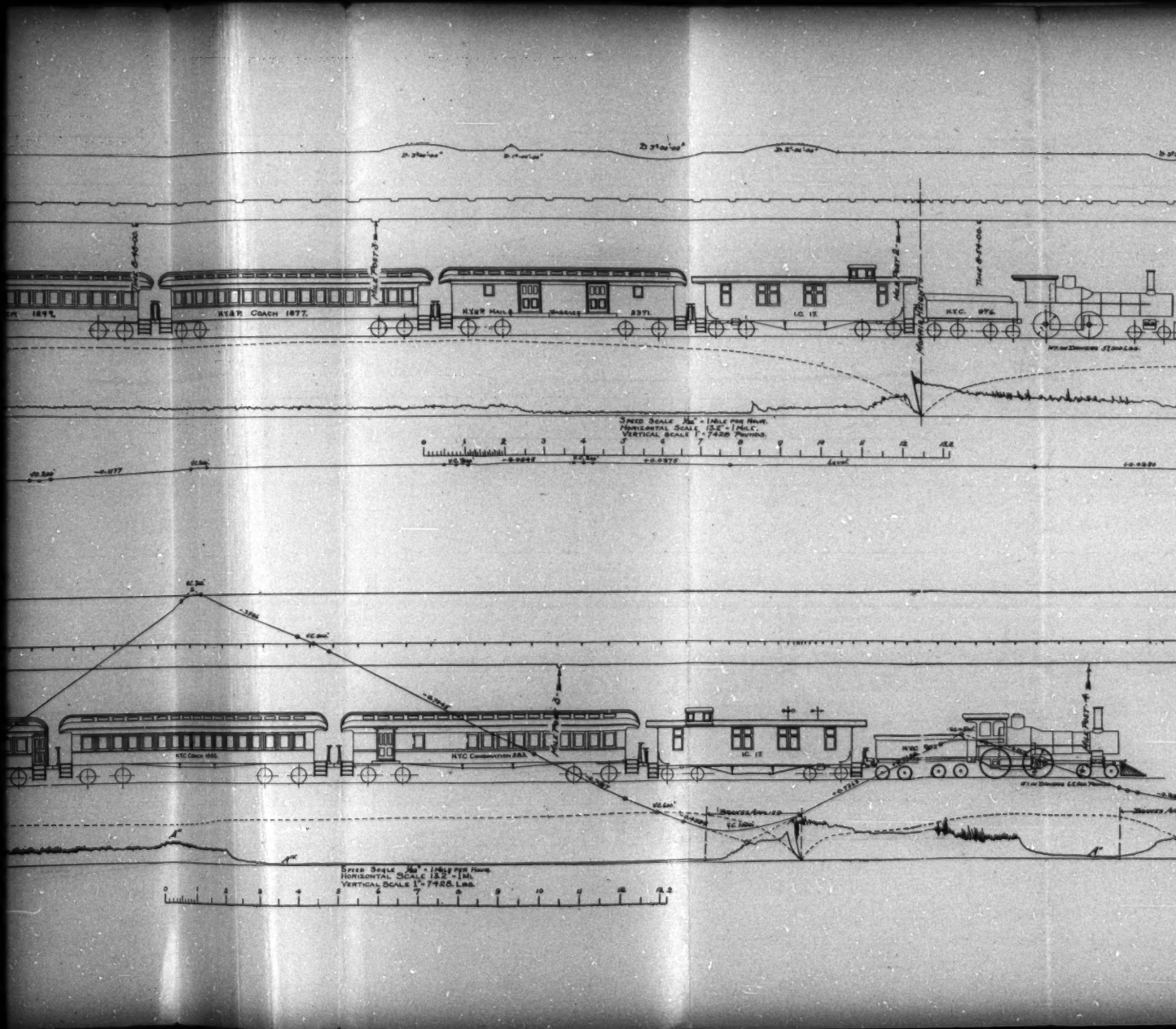
The dynamometer cylinders and a diagrammatic arrangement of the car are shown in Fig. 6. The cylinders are made of three castings held together by stud bolts not shown in the figure. The effective area of the largest cylinder is 60 sq. in., of the intermediate cylinder 30 sq. in., and of the smallest 5 sq. in. It is intended that the working pressure of the oil in the cylinder shall be from 300 to 1,000 lbs., per square inch, and for this range of pressure the largest cylinder has sufficient capacity for the heaviest freight service, the intermediate cylinder being used when working with a train of ordinary tonnage, and the smallest cylinder when working with a train of light tonnage. If it should become necessary all the cylinders could be coupled up in multiple, thus giving an effective piston area of 95 sq. in.

The cylinders are reamed and the pistons and piston rods ground. The forward end of the gland is ground spherical and fits into a spherically ground seat in the stuffing box casting. This spherical seat is used to permit the three sleeves to align themselves properly on the rod. The pressure of the oil keeps the gland on its seat and this oil pressure is supplemented by the pressure of several helical springs placed between the rear end of the sleeve and the plate shown at the inner end of the stuffing box. The pistons will gradually move forward on account of leakage, but so slowly that the cylinders can be refilled from the pump at stops, or if necessary, when the cylinders are under pressure. This design was resorted to in order to avoid the uncertainty concerning the frictional resistance incident to the use of the usual packed pistons and stuffing boxes.

In Fig. 5 is shown the table upon which are placed the dynamometer recording gauge, the rolls for driving the paper chart and


Mile Post 5
Time 8-46-00
N.Y.&P. SMOKER 1292
N.Y.C. COACH 1882
N.Y.C. COACH 188
Grade Compensated for Curvature


N.Y.&R. Coach 1977.
N.Y.&R. Mail & Baggage 2371
M.C. 17.
N.Y.C. 976.
Speed Scale 1/16" = 1 Mile per Hour.
Horizontal Scale 1.2" = 1 Mile.
Vertical Scale 1" = 7428 Pounds.
N.Y.C. Combination 283.
M.C. 17.
Speed Scale 1/16" = 1 Mile per Hour.
Horizontal Scale 1.2" = 1 Mi.
Vertical Scale 1" = 7428 Lbs.


N.Y.&P. Coach 1877.
N.Y.C. 974.
I.C. 1X
Speed Scale 1/8" = 1 Mile per Hour.
Horizontal Scale 13.2" = 1 Mile.
Vertical Scale 1" = 7425 Pounds.
N.Y.C. Coach 1885.
N.Y.C. Combination 283.
I.C. 1X
Speed Scale 1/8" = 1 Mile per Hour.
Horizontal Scale 13.2" = 1 Mi.
Vertical Scale 1" = 7425 Lbs.

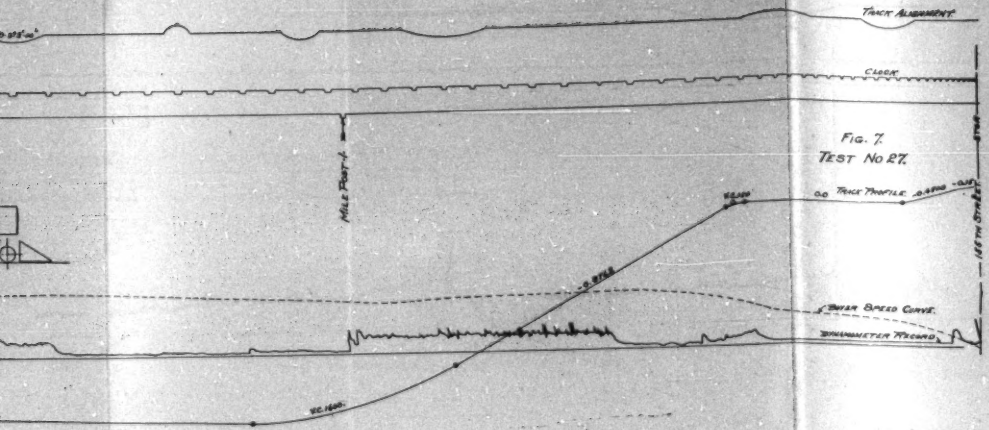


FIG. 7.—TEST NO. 27.

Putnam Junction to 155th St., Putnam Division.
Railway Test Car No. 17, November 5th, 1901
Passenger Train No. 2.
30 sq. in. cylinder in operation, test car backward.

Engine 976 N. Y. C.			
Weight of engine loaded			45.15 tons
Weight on drivers			28.65 "
Total Weight loaded engine and tender			80.15 "
Train as follows:			
17	I. C.	Test Car	
2371	N. Y. & P.	Mail and Baggage	48,200 lbs.
1877	"	Coach	47,700 "
1299	"	Smoker	53,050 "
			74.0 tons
		Passengers	8. "
			82.0 tons

Weather.—Cool and cloudy at start, light rain, commenced at 7 30 and continued to end of test, temperature 40 F. Passenger and Anemometer records taken.
Rail good.

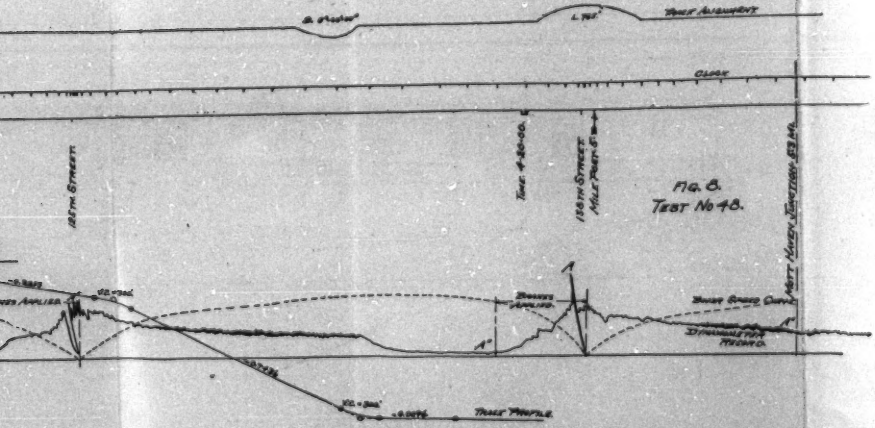
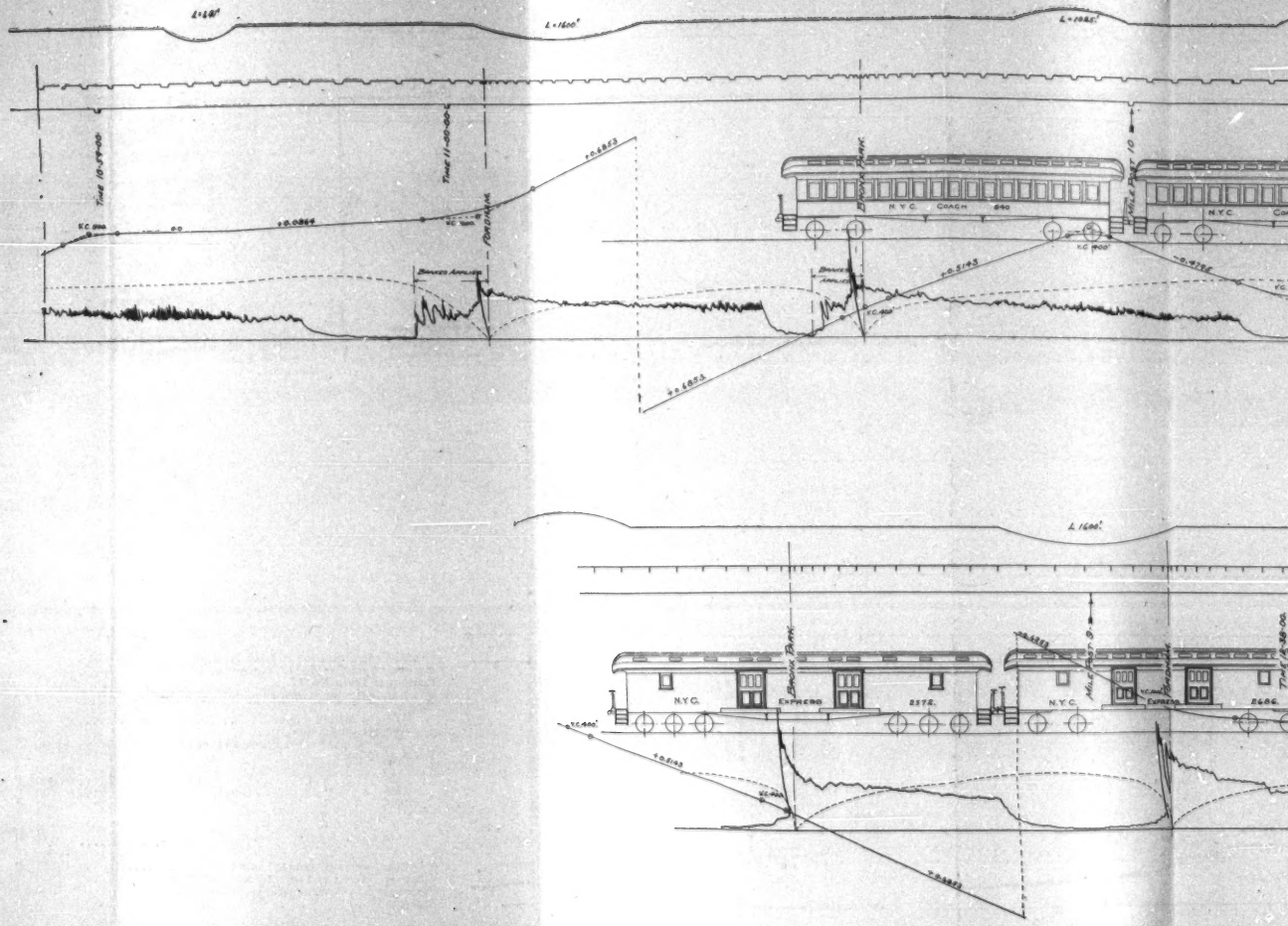


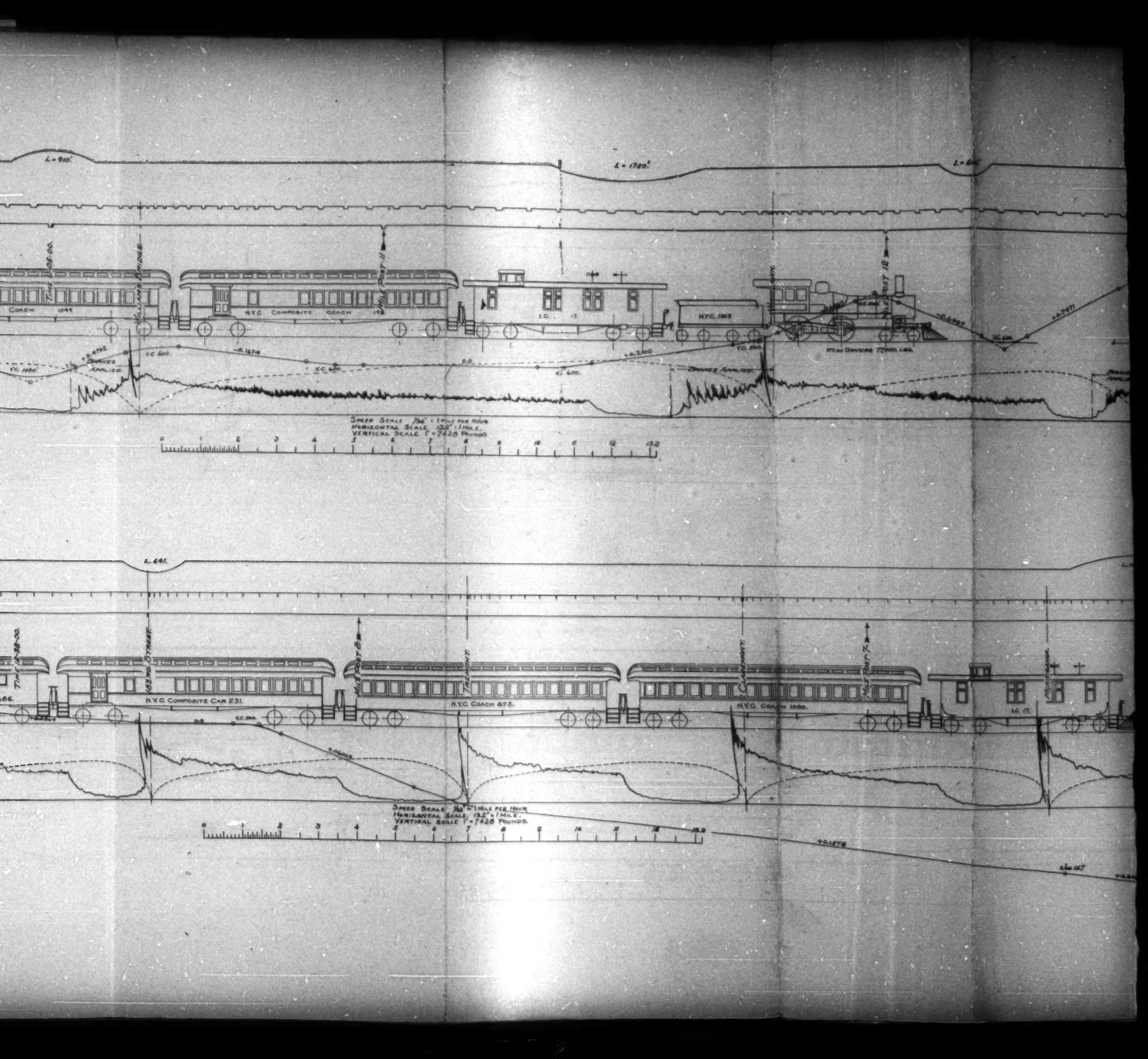
FIG. 8.—TEST NO. 48.

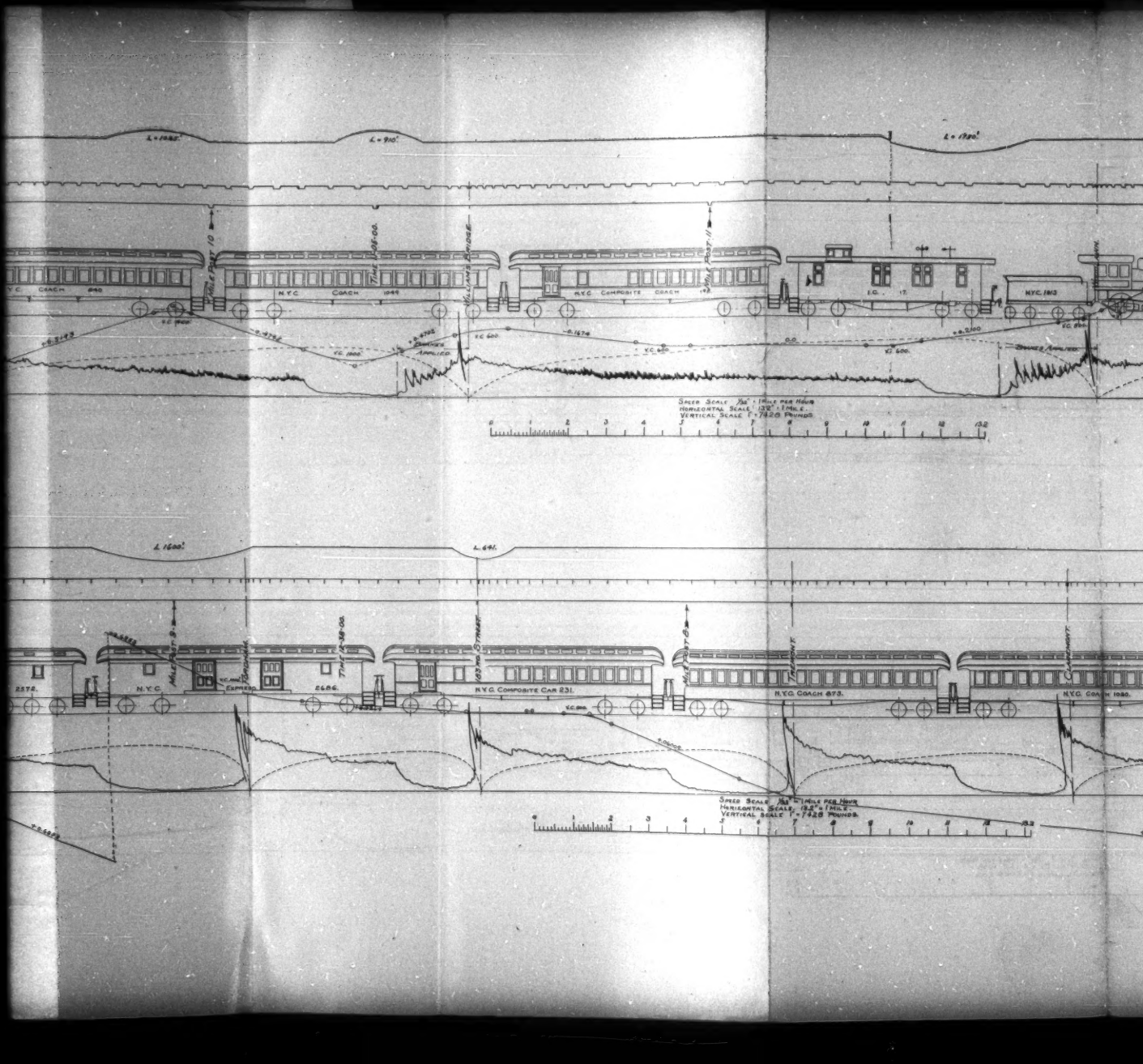
Grand Central Station to Lake Mahopac, Harlem Division.
Railway Test Car No. 17, November 14th, 1901.
Passenger Train No. 17.
30 sq. in. cylinder in operation test car forward.

Engine 987 N. Y. C.			
Weight loaded engine			49.25 tons.
Weight on drivers			32.75 "
Total weight loaded engine and tender			84.6 "
Train as follows:			
17	I. C.	Test Car	44,656 lbs.
283	N. Y. C.	Combination	50,600 "
1026	"	Coach	65,100 "
1087	"	"	86,500 "
			127.9 tons.
		Passengers	9.4 "
		Total tonnage included in record	137.3 "

Weather.—Clear and dry, temperature 43 F.
Passenger and Anemometer records taken.
Rail good.


L=1600'
L=1600'
L=1600'
Time 10-37-00
Time 11-00-00
Brakes Applied
+0.0823
+0.0823
+0.0823
N.Y.C. COACH 890
N.Y.C. COACH 2572
N.Y.C. EXPRESS 2572
N.Y.C. EXPRESS 2686
Brakes Applied
Brakes Applied
Brakes Applied
Brakes Applied
-0.0743
-0.0743
+0.0823
+0.0823
+0.0823
+0.0823
+0.0823
+0.0823


L = 910'
L = 1700'
L = 600'
Time 10:35:00.
Williams Bridge
Mile Post 11
Coach 1049
N.Y.C. Composite Coach 178
I.C. 17
N.Y.C. 1913
Mile Post 12
Mt. 4th Drivers 72"
Speed Scale 1/16" = 1 Mile per Hour
Horizontal Scale 1/2" = 1 Mile.
Vertical Scale 1" = 7428 Pounds.
L = 641'
Time 10:38:00.
163rd Street
Mile Post 6
Tremont
Claremont
Mile Post 7
Hunts Point
N.Y.C. Composite Car 231
N.Y.C. Coach 873.
N.Y.C. Coach 1080.
I.C. 17.
Speed Scale 1/16" = 1 Mile per Hour
Horizontal Scale, 1/2" = 1 Mile.
Vertical Scale 1" = 7428 Pounds.


N.Y.C. COACH 940
N.Y.C. COACH 1049
N.Y.C. COMPOSITE COACH 193
I.C. 17
N.Y.C. 1813
SPEED SCALE 1/64" = 1 MILE PER HOUR
HORIZONTAL SCALE 1/2" = 1 MILE.
VERTICAL SCALE 1" = 7420 POUNDS.
N.Y.C.
N.Y.C. COMPOSITE CAR 231.
N.Y.C. COACH 873.
N.Y.C. COACH 1080.
SPEED SCALE 1/64" = 1 MILE PER HOUR
HORIZONTAL SCALE 12.5" = 1 MILE.
VERTICAL SCALE 1" = 7420 POUNDS.

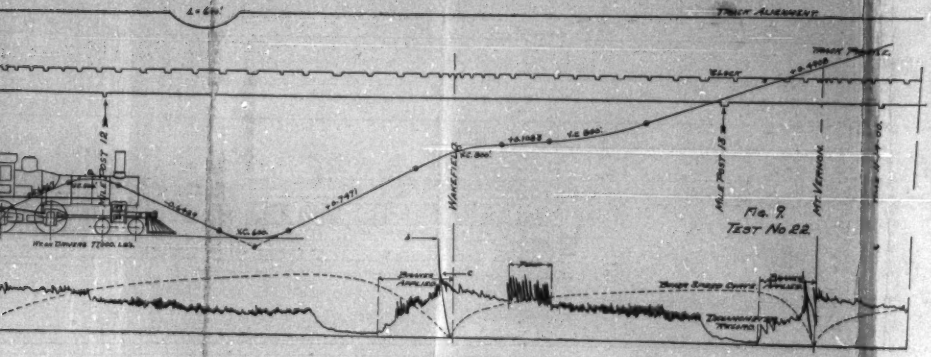


FIG. 9.—TEST NO. 22.

Grand Central Station to White Plains, Harlem Division
Railway Test Car No. 17, November 2d, 1901.
Passenger Train No. 111.
30 sq. in. cylinder in operation, test car forward.
Engine 1013 N. Y. C.

Weight of loaded engine	55.	tons
Weight on drivers	38.5	"
Total weight loaded engine and tender	95.7	"

Train as follows:

17	L. C.	Test Car	44,650 lbs.
192	N. Y. C.	Combination	63,800 "
1049	"	Coach	54,340 "
840	"	"	57,900 "
			125.4 tons
		Passengers	15. "
		Total tonnage included in record	140.4 "

Weather.—Fine, clear, temperature 61–68 F.
Wind very light, direction not noted.
Rail good

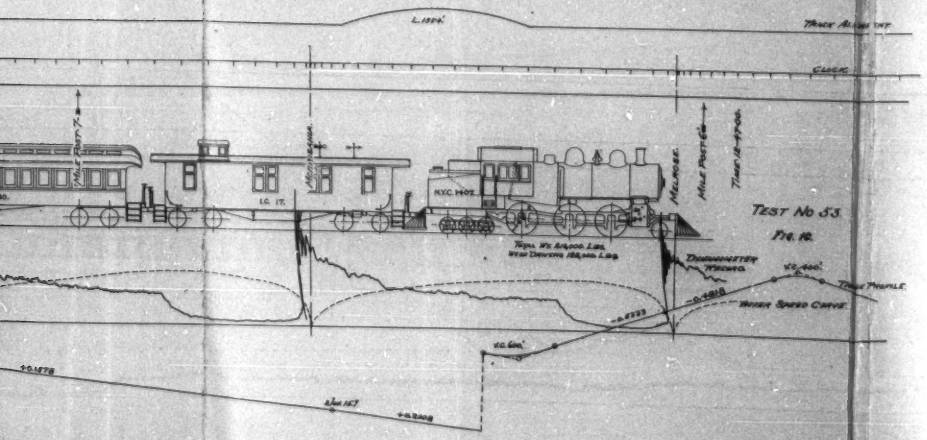


FIG. 10.—TEST NO. 53

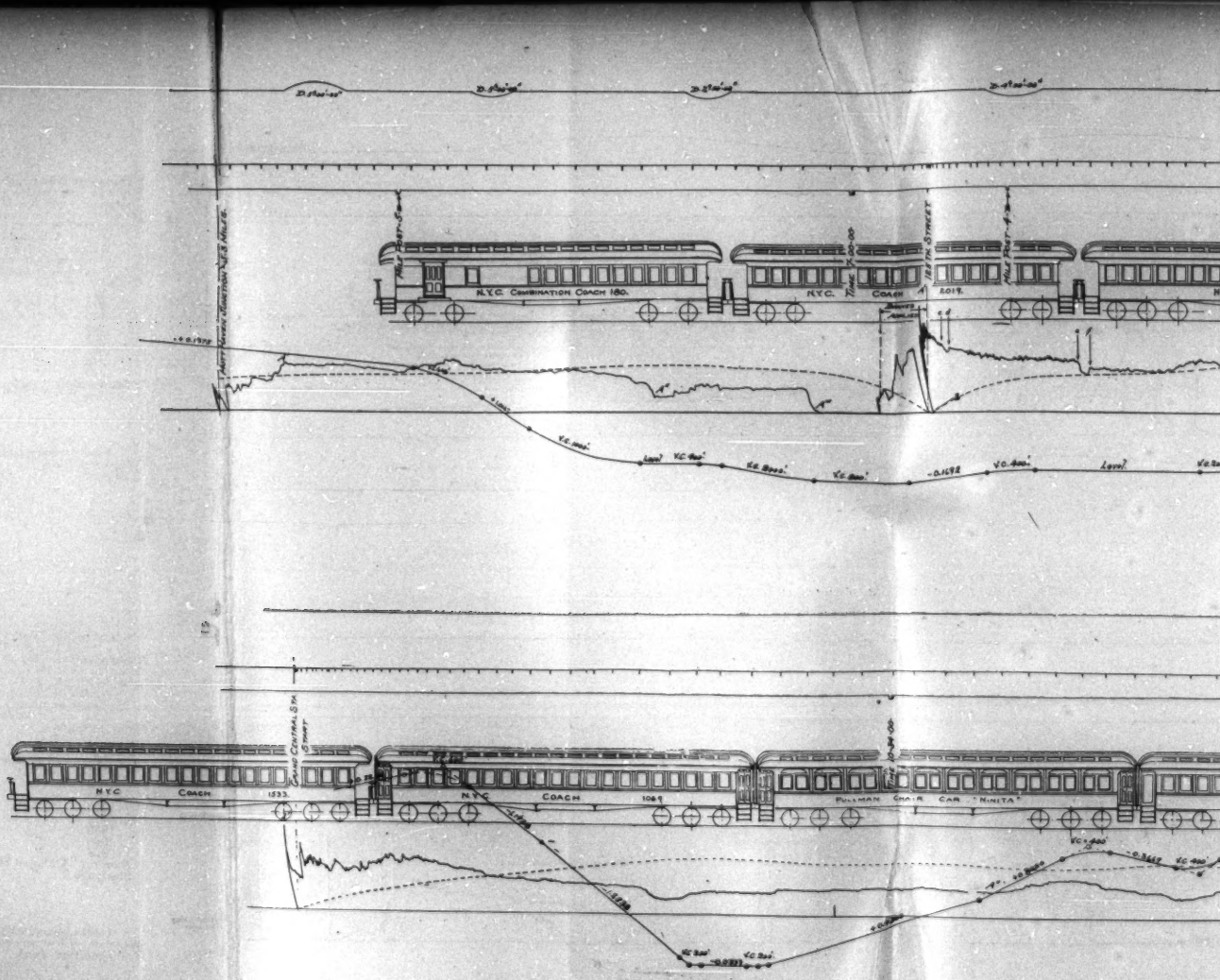
White Plains to Grand Central Station, Harlem Division.
Railway Test Car No. 17, November 19th, 1901.
Passenger Train 130.
30 sq. in. cylinder in operation, test car forward
Engine 1407 N. Y. C.

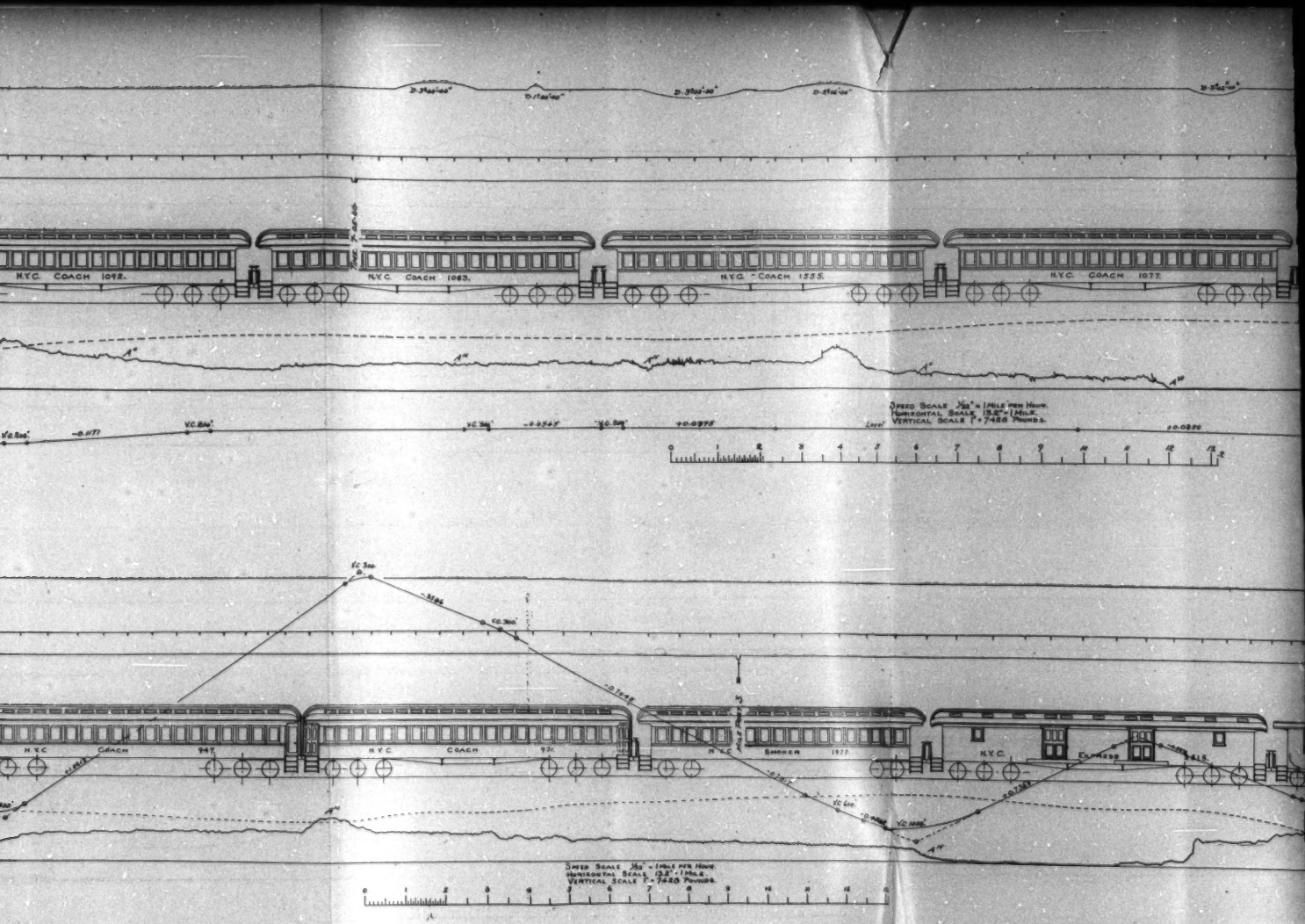
Total weight	108	tons
Weight on drivers	64	"
Weight with tender	108	"

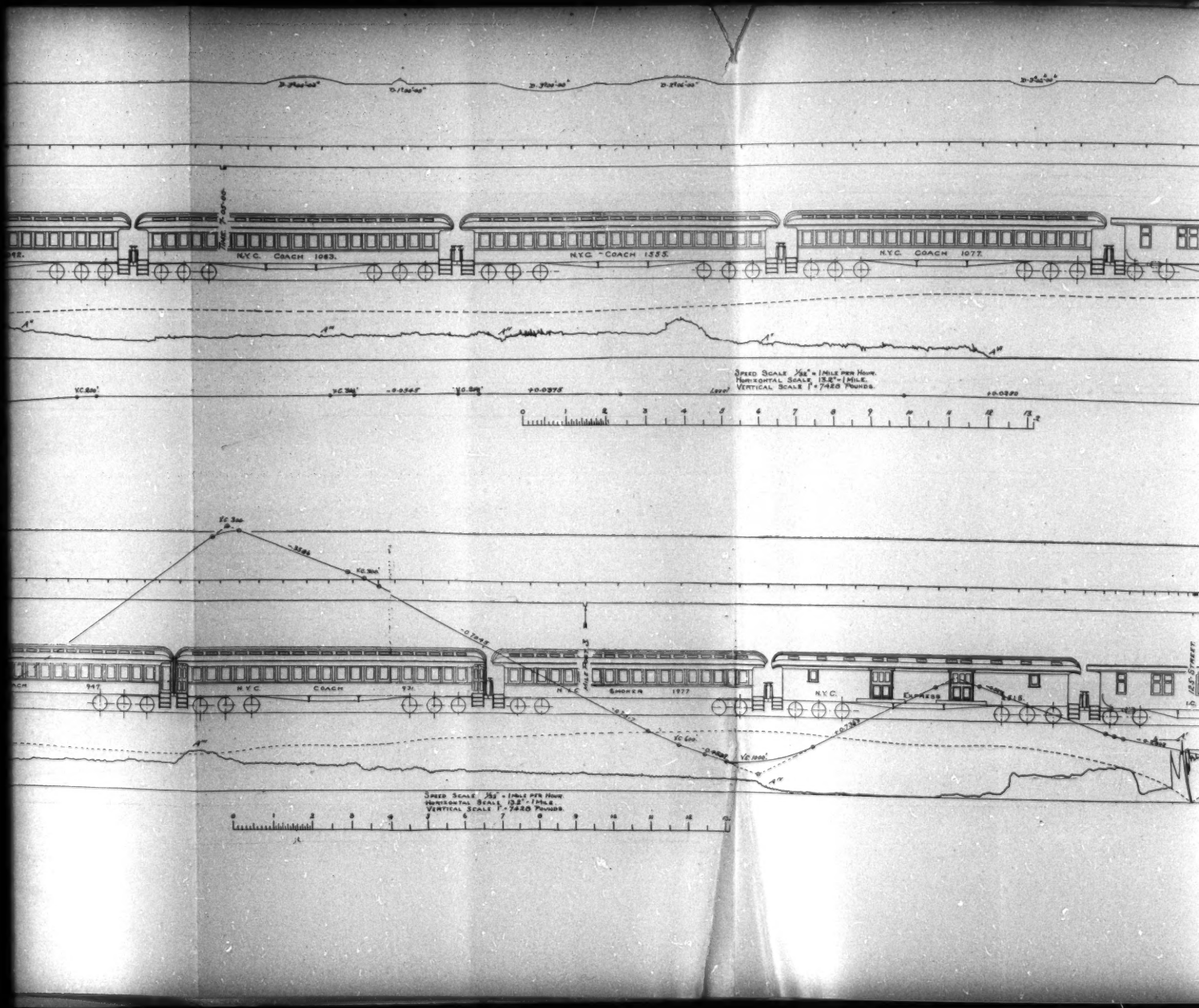
Train as follows:

17	L. C.	Test Car	44,650 lbs.
1020	N. Y. C.	Coach	65,500 "
873	"	"	60,900 "
231	"	Combination	60,300 "
2686	"	Express	54,300 "
2572	"	"	81,000 "
			183.3 tons.
		Passengers	36.6 "
		Total tonnage included in record	220.0 "

Weather.—Clear and dry, temperature 43 F.
Passenger and Anemometer records taken.
Rail good


N.Y.C. Combination Coach 180.
N.Y.C. Coach
125th Street
Grand Central 57th Street
N.Y.C. Coach 1533
N.Y.C. Coach 1089
Pullman Chair Car "Ninita"


N.Y.C. COACH 1092.
N.Y.C. COACH 1063.
N.Y.C. COACH 1355.
N.Y.C. COACH 1077.
SPEED SCALE 1/32" = 1 MILE PER HOUR.
HORIZONTAL SCALE 13.2" = 1 MILE.
VERTICAL SCALE 1" = 7420 POUNDS.
N.Y.C. COACH 947.
N.Y.C. COACH 936.
N.Y.C. SMOKER 1077.
N.Y.C. EXPRESS
SPEED SCALE 1/32" = 1 MILE PER HOUR.
HORIZONTAL SCALE 13.2" = 1 MILE.
VERTICAL SCALE 1" = 7420 POUNDS.


N.Y.C. COACH 1083.
N.Y.C. COACH 1555.
N.Y.C. COACH 1077.
SPEED SCALE 1/32" = 1 MILE PER HOUR.
HORIZONTAL SCALE 13.2" = 1 MILE.
VERTICAL SCALE 1" = 7425 POUNDS.
N.Y.C. COACH
N.Y.C. SMOKER 1977
N.Y.C. EXPRESS
SPEED SCALE 1/32" = 1 MILE PER HOUR.
HORIZONTAL SCALE 13.2" = 1 MILE.
VERTICAL SCALE 1" = 7425 POUNDS.

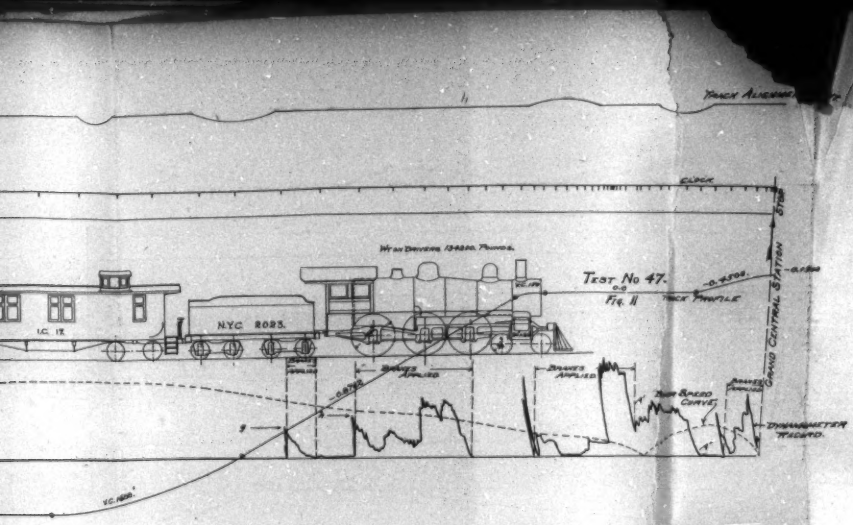


FIG. 11.—TEST NO. 47.

Poughkeepsie to Grand Central Station, Hudson Division.
Railway Test Car No. 17, November 13th, 1901.
Passenger Train No. 2.
30 sq. in. cylinder in operation, test car backward.
Engine 2023 N. Y. C.

		Weight of loaded engine	87.5 tons.
		Weight on drivers	67.15 "
		Total weight with loaded engine and tender	143.5 "

Trains as follows:

17	I. C.	Test Car	45,640 lbs.
1077	N. Y. C.	Coach	85,500 "
1555	"	"	84,400 "
1063	"	"	86,300 "
1092	"	"	86,600 "
2019	"	"	60,100 "
180	"	Combination	65,600 "
			234.5 tons.
		Passengers	33.3 "
		Total tonnage included in record	267.8

Weather.—Fair and dry temperature 52 to 59 F.
Passenger and Anomometer records taken.
Rail damp.

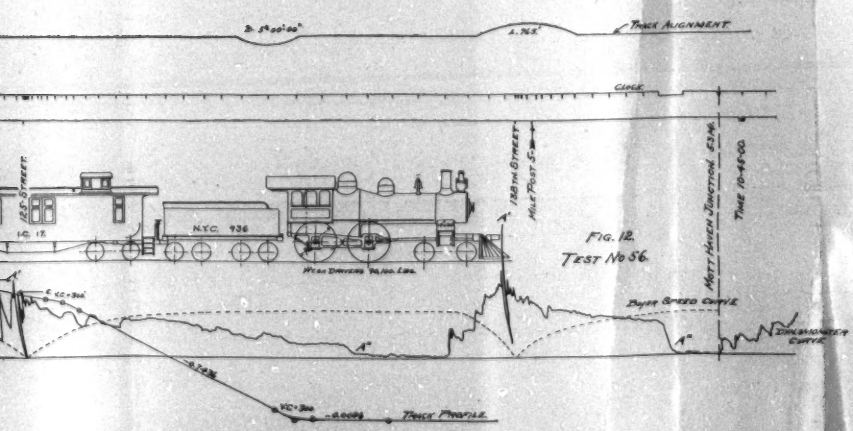


FIG. 12.—TEST NO. 56.

Grand Central Station to Schenectady, Hudson & Mohawk Divisions.
Railway Test Car No. 17, November 20th, 1901.
Passenger Train No. 7.
30 sq. in. cylinder in operation, test car running backward.
Engine 936 N. Y. C.

		Weight of loaded engine	67.3 tons.
		Weight on drivers	45.0 "
		Total weight loaded engine and tender	114.1 "

Train as follows:

17	I. C.	Test Car	——— lbs.
2515	N. Y. C.	Express	77,800 "
1977	"	Smoker	65,500 "
931	"	Coach	88,300 "
947	"	"	93,000 "
"Ninita"	Pullman	Chair Car	100,000 "
1069	N. Y. C.	Coach	84,400 "
1533	"	"	84,400 "
			16.7 tons.
		Passengers	294.8 "
		Total tonnage included in record	311.5 "

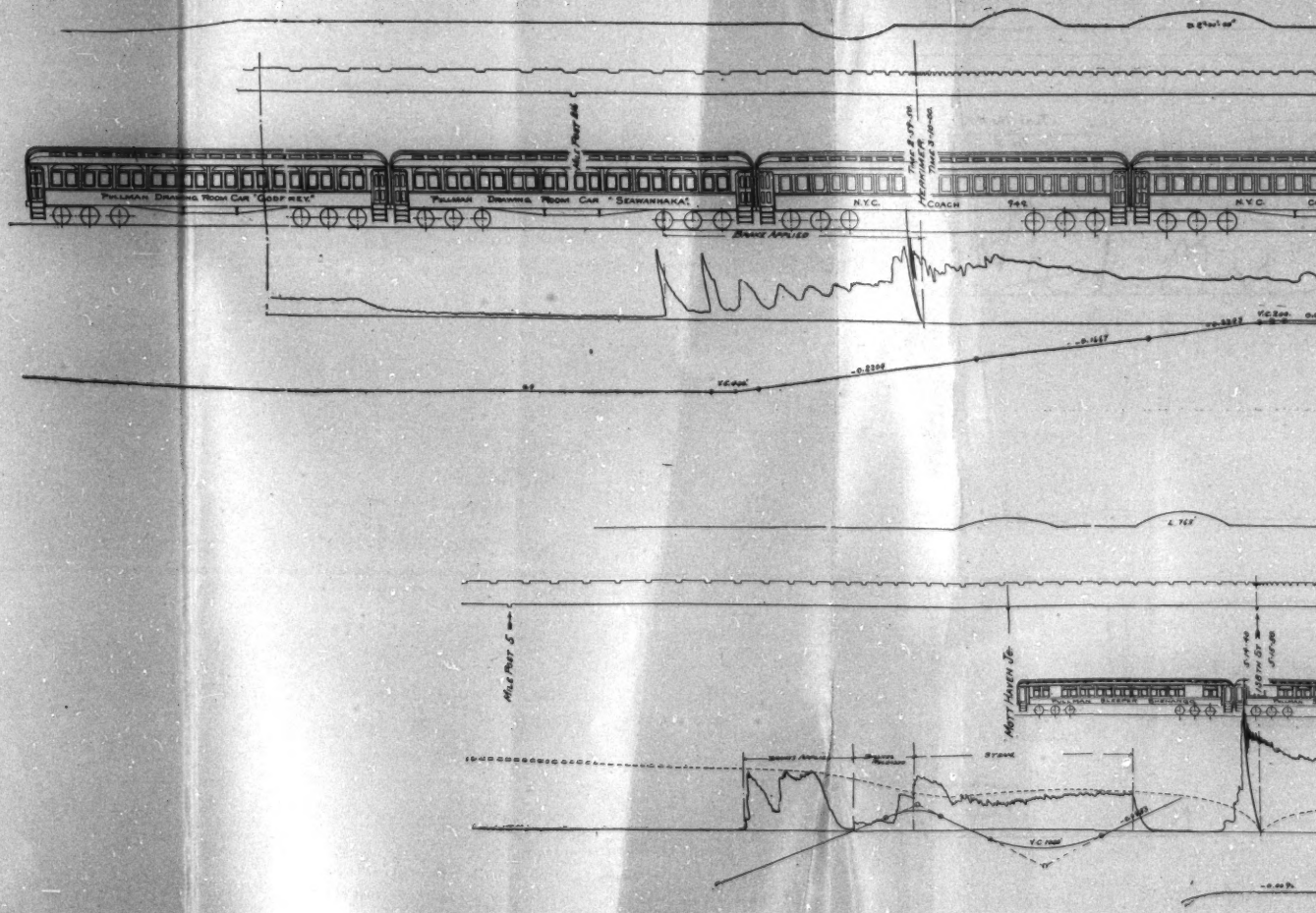
Poughkeepsie.

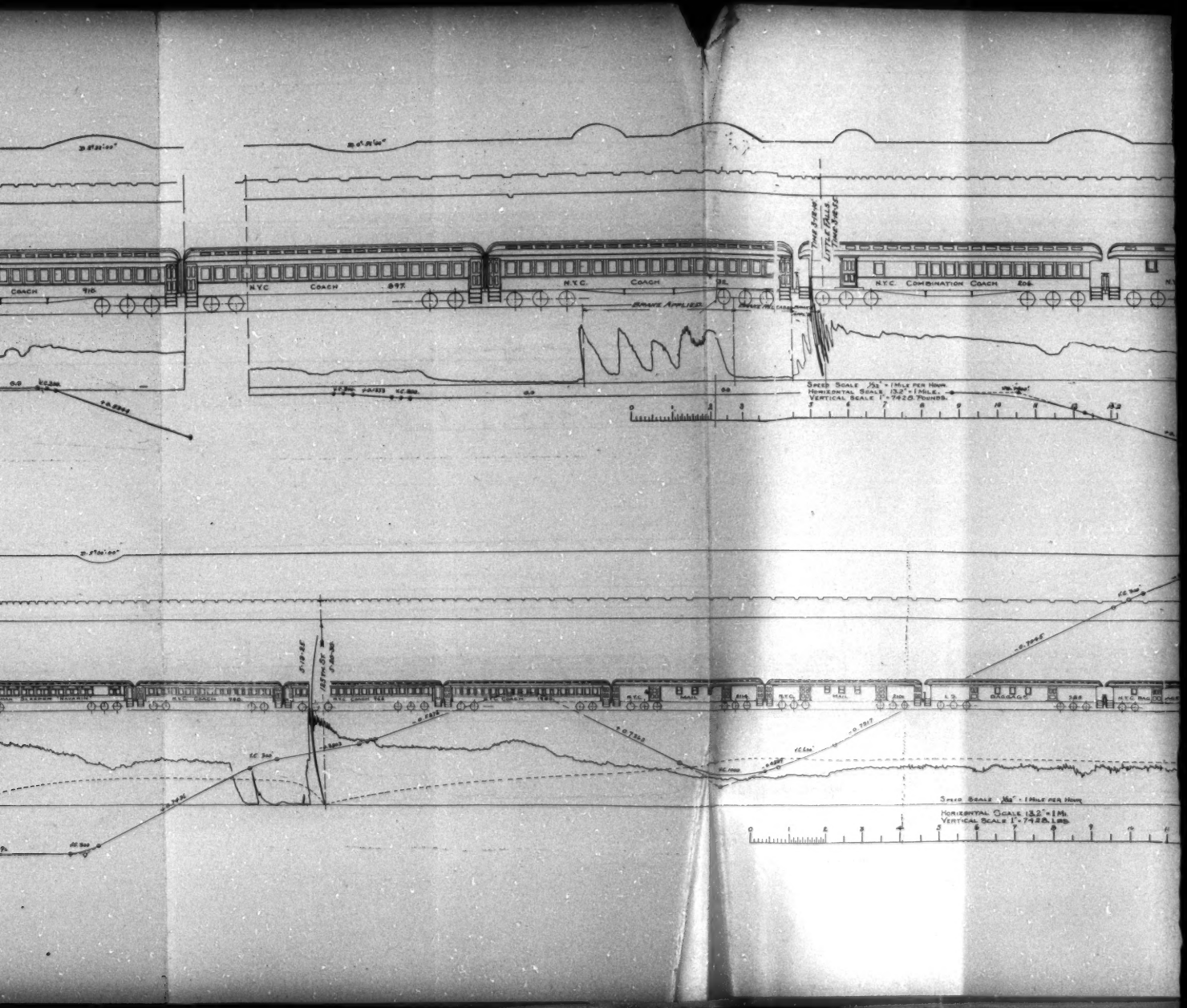
1533	N. Y. C.	Coach.	Set Out.
210	"	Comb.	Taken On.

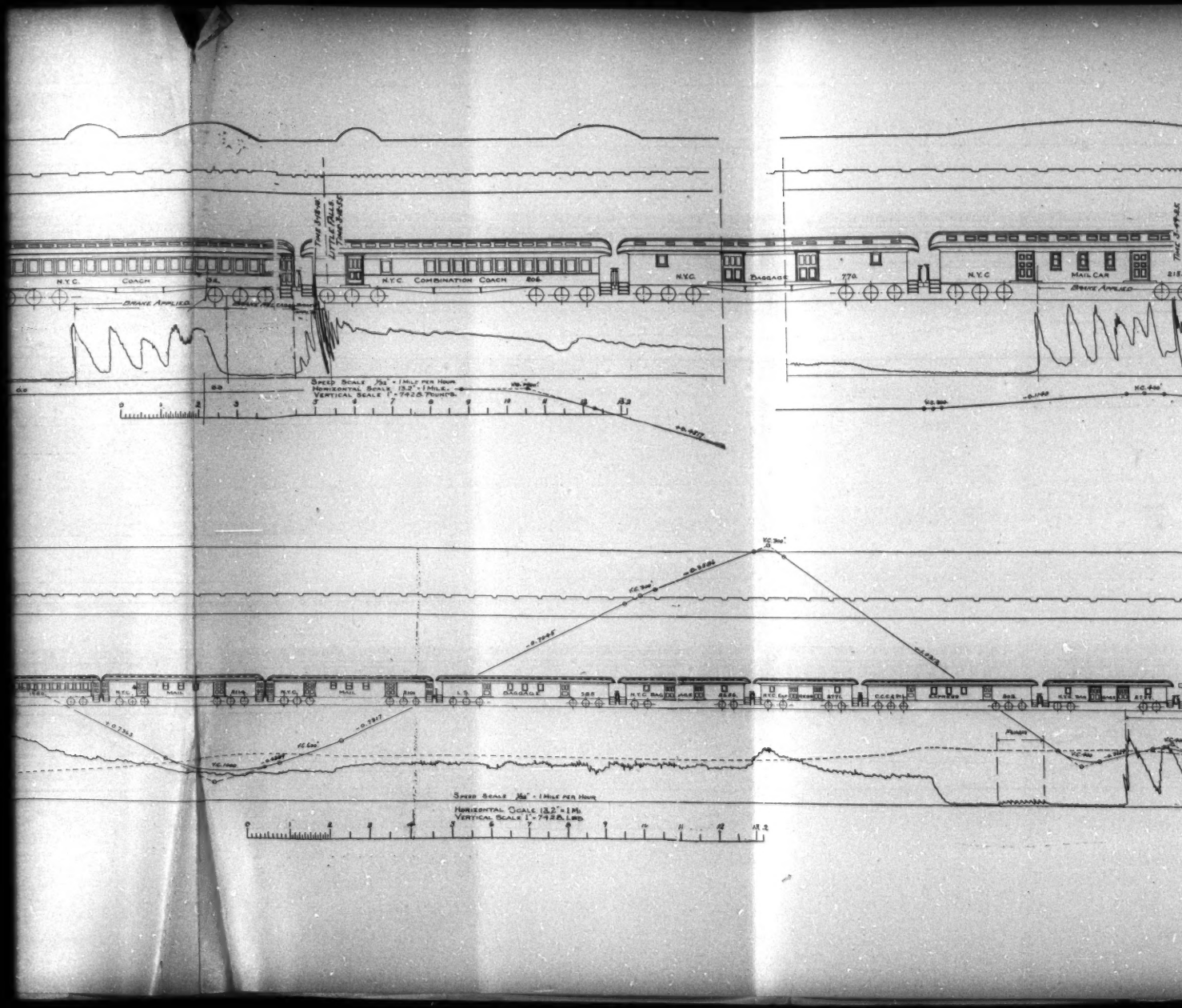
Albany:

936	"	Engine.	Taken Off.
2018	"	"	Taken On.
1069	"	Coach.	Set Out.
210	"	Comb.	" "

Weather.—Clear, temperature 35 F.
Passenger and Anemometer records taken.
Rail good.
NOTE.—Calibration tests were made on the run between Albany and Schenectady.
NOTE.—When Dynamometer Car is running "forward" or "backward" its weightis or is not included in the Dynamometer Record.


PULLMAN DRAWING ROOM CAR "GODFREY"
PULLMAN DRAWING ROOM CAR "SEAWANHAKA"
N.Y.C.
COACH
949
N.Y.C.
BRAKE APPLIED
MILE POST 5
MOTT HAVEN JC.
MILE POST 5


COACH 916
N.Y.C. COACH 897
N.Y.C. COACH 98
N.Y.C. COMBINATION COACH 206
BRAKE APPLIED
TIME STEM AT LITTLE FALLS TIME STATION
SPEED SCALE 1/32" = 1 MILE PER HOUR.
HORIZONTAL SCALE 13.2" = 1 MILE.
VERTICAL SCALE 1" = 7428 POUNDS.
N.Y.C. COACH 926
N.Y.C. COACH 928
N.Y.C. COACH 908
N.Y.C. MAIL 604
N.Y.C. MAIL 605
L.V. BAGGAGE 288
N.Y.C. BAGGAGE
SPEED SCALE 1/32" = 1 MILE PER HOUR
HORIZONTAL SCALE 13.2" = 1 MI.
VERTICAL SCALE 1" = 7428 LBS.


N.Y.C. COACH
BRAKE APPLIED
N.Y.C. COMBINATION COACH
N.Y.C. BAGGAGE
N.Y.C. MAIL CAR
SPEED SCALE 1/32" = 1 MILE PER HOUR
HORIZONTAL SCALE 13.2" = 1 MILE.
VERTICAL SCALE 1" = 742.8 POUNDS.
SPEED SCALE 1/64" = 1 MILE PER HOUR
HORIZONTAL SCALE 13.2" = 1 MI.
VERTICAL SCALE 1" = 742.8 LBS.

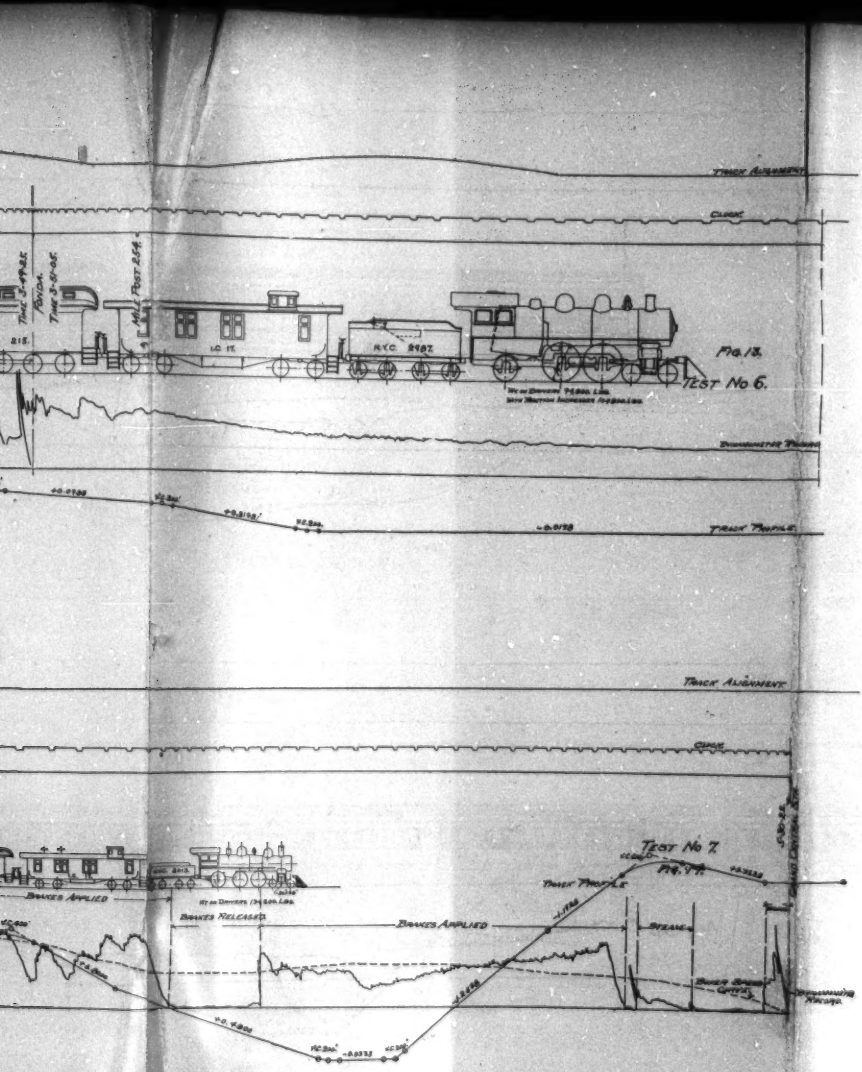


FIG. 13.—TEST NO. 6.

Syracuse to Albany, Mohawk Division
Railway Test Car No. 17, Oct. 25th, 1901.
Passenger Train No. 14.
30 sq. in. cylinder in operation, test car backward.
Engine 2987 N. Y. C.

Weight of loaded engine	88.	tons.
Weight on drivers	47.4	"
Using traction increaser	52.4	"
Total weight loaded engine and tender	144.5	"

Train as follows:

17	I. C.	Test Car	———	lbs.
215	N. Y. C.	Mail	56,300	"
770	"	Baggage	60,000	"
206	"	Combination	84,000	"
932	"	Coach	87,000	"
897	"	"	58,200	"
910	"	"	87,700	"
949	"	"	94,500	"
" Seawanhaka "	Pullman	Drawing Room Car	89,000	"
" Godfrey "	"	" " " "	87,300	"
			337.0	tons.
		Passengers	17.0	"
		Total tonnage included in record	354.0	"

Weather.—Clear.
Rail good.

FIG. 14.—TEST NO. 7

Chicago to New York.
Railway test Car No. 17, Hudson Division.
Passenger Train No. 28.
30 sq. in. cylinder in operation, test car running backward
Engine 2013 N. Y. C.

Weight of loaded engine	87.6	tons.
Weight on drivers	67.15	"
Total weight loaded engine and tender	143.5	"

Train as follows:

17	I. C.	Test Car	———	lbs.
2739	N. Y. C.	Baggage	59,000	"
202	C. C. C. & St. L.	Express	50,000	"
2771	N. Y. C.	"	44,500	"
2656	"	Baggage	52,500	"
585	"	"	59,100	"
2106	"	Mail	86,000	"
2114	"	"	80,100	"
1980	"	Coach	70,000	"
966	"	"	94,800	"
928	"	"	67,900	"
" Navarin "	Pullman	Sleeper	108,000	"
" Shenango "	"	"	97,000	"
			434.45	tons.
		Passengers	21.72	"
		Total tonnage included in record	456.17	"

Weather.—Clear and cool, wind light, direction not noted.
Rail condition good

the Boyer speed recorder. The vertical shaft projecting through the floor under the middle of the table derives its motion from the car axle by means of worm and bevel gears. Its motion is transmitted by means of the gears shown, to the speed recorder and the paper driving apparatus. This consists of a pair of driving rolls, around which the paper passes, and supply and receiving rolls. The paper is drawn from the former and fed to the latter after running over the drum of the recorder.

DISCUSSION OF DYNAMOMETER RECORDS.

Figs. 7 to 14 inclusive show the dynamometer car records of eight different classes of trains which are in daily operation over some of the divisions of the road. On each record is shown graphically the following:

(1) The "draw-bar pull" of train shown in the irregular heavy line as recorded by the pen of the dynamometer cylinder, each inch of height from the base line being equivalent to 7,428 pounds of draw-bar pull exerted by the engine on the train, which is shown in outline on the record, the horizontal scale being 13.2 inches to the mile.

(2) The speed of the train is shown by the regular dotted line, each thirty-second of an inch of height representing a speed of one mile per hour.

(3) The profile of the road is shown at the bottom and the alignment at the top of each record, so that it is possible to calculate by formulæ the theoretical horse power required to haul the train under the conditions of each case and after equating for grade and curvature, check the result by the curves here given.

It should be noted that the records do not include the power required to propel the locomotive nor the head-end resistance offered to it by the air, and that when the dynamometer car was running backward, the power to propel it is not represented in the record and its weight should not be taken into consideration as a part of the train. These factors were taken into account when determining the final load diagram.

The diagrams are arranged in the order of the train weights with the light trains first, and a few trains have been introduced which do not operate over the particular division under consideration.

Fig. 7 represents a light suburban train running on the New York & Putnam Division from Putnam Junction to 155th Street.

Fig. 8 represents a light suburban train of the Harlem Division which runs between Grand Central Station and Lake Mahopac.

Fig. 9 represents a suburban train which runs on the Harlem Division between Grand Central Station and White Plains.

Fig. 10 shows a moderate weight suburban train of the Harlem Division which runs between White Plains and Grand Central Station.

Fig. 11 represents a standard local through train on the Hudson Division known as the Day Express, stopping at practically all stations.

Fig. 12 represents a through local train known as the Day Express, which stops at nearly all stations.

Fig. 13 represents a through fast train running between Buffalo and Albany, known as the New York & New England Express, which makes the fastest through time between Chicago and New York and Boston made by any train on the road.[1] This record is introduced as an interesting example of the requirements of heavy through train service and as a part of the record taken on a through run from Chicago to New York, a distance of nearly one thousand miles.

The train was hauled by the latest type of New York Central passenger locomotive, which has hauled a train of sixteen cars, weighing with the locomotive over 900 tons, at a speed of 60 miles per hour, and maintained the schedule speed of over 45 miles per hour with the same train between New York and Albany.

On the run from which Fig. 13 was taken, the engine maintained for a considerable distance a speed of 63 miles per hour, with 10 cars, constituting with the engine a train weighing 494 tons, thus developing continuously 940 h.p., assuming the ordinary allowance for head-end resistance due to wind or air pressure. At another time and with a heavier train, this engine developed 1,452 i.h.p., at 63 miles per hour, 240 r.p.m., as shown by indicator cards.

Fig. 14 represents the record from Mott Haven Junction to Grand Central Station of a through heavy express train known as the New York & Boston Express, loaded heavily with express matter, mail and papers, but carrying few passengers.

It is thought that the records here introduced are sufficient in number and character to represent fairly well the various classes of duty required of the present steam locomotives, and what would be required from electric locomotives in case they should be adopted, as the problem submitted was to duplicate

1. Since writing this, the new 20-hour train known as the "Twentieth Century Limited" between New York and Chicago has been put in service.

the present passenger train service between Mott Haven Junction and Grand Central Station, by using electric power instead of steam locomotives.

The questions of changes in the Grand Central terminal, or of the present method of train operation, or of handling the suburban trains on the division outside of Mott Haven Junction are not considered in this paper.

It appears that the braking effort per ton is not as high on certain types of locomotives as it is on coaches. This is due to the fact that not all the wheels of the locomotive are always braked, and those that are braked cannot be set to the skidding point with a fully loaded tender, for if they were they would then skid with a lightly loaded tender. Hence the draw-bar pull during retardation is often as great, or even greater than it is during acceleration. An instance of this is seen in Fig. 12 at (*b*), where the maximum draw-bar pull due to the braking effort of the train on the locomotive is 11,950 lbs., while the maximum draw-bar pull exerted in starting the train at (*c*) is 9,945 lbs. That is to say, in this particular run during the period over which all possible retardation is desired, the draw-bar pull instead of being zero, is 20% greater than that available for acceleration. In Fig. 9, for the stop at Wakefield these figures become respectively 15,675 lbs., 9,899 lbs. and 60%. At all other stops on this record it is seen that the braking effort of the train is nearly equal to the maximum starting effort of the locomotive during acceleration.

The severe oscillation of the dynamometer pen on this record exhibits the irregular turning moment of the engine which is caused partly by unequal distribution of the steam in the cylinders, due to the lack of proper adjustment of the valve motion, and partly to the irregular turning moment of any two-cylinder engine of this type.

In Fig, 10, however, which is the record obtained from engine No. 1407—one of the latest type of suburban engines on this road —the smoothness of the record, and the perfect braking of the engine and train are noticeable.

Where these records are marked "pump," the dynamometer cylinder was being filled with oil from the hand pump provided for this purpose.

The various phases in the cycle of locomotive performance are clearly seen in the dynamometer records; thus, in Fig. 11, at (*b*) the engine was given steam, at (*c*) hooked up, and at (*d*)

given more steam, at (*e*) again hooked up, and at (*f*) again given more steam; at A[VI] steam was cut off and the train coasted to (*g*) where brakes were applied, released, and again applied at (*h*), etc., etc.

METHOD OF OBTAINING HORSE POWER AT DRAW-BAR FROM DYNAMOMETER RECORDS.

This was obtained in general in the following manner: From

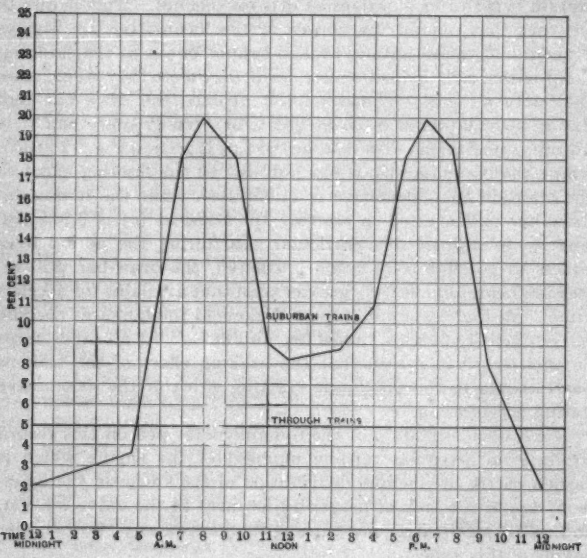


FIG. 15

Percentage of Passenger weight to Light Train weights, Grand Central Station to Mott Haven Junction.

actual dynamometer car tests the average draw-bar pull of the various trains over the various runs was determined, proper allowance made for increased train weight due to motor equipment, and finally a reduction of the draw-bar pull thus obtained to horse-power, and eventually to kilowatts. Owing to the fact that the maximum speeds on this division seldom exceed 35 miles per hour and that the trains were never less than three

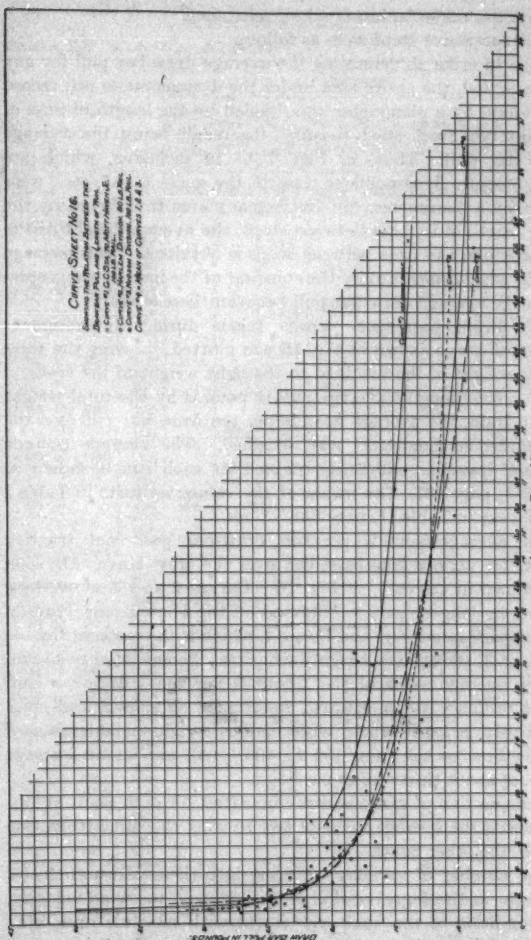


FIG. 16.

cars in length—often reaching eleven cars in length—no correction was made for head-end air resistance.

The successive steps were as follows:

(1) In order to determine the average draw-bar pull for any given period, the entire area under the dynamometer pen record was found by a planimeter and divided by the length of base of the interval from start to stop, the result being the average draw-bar pull. Thus, in Figs. 7 to 14 inclusive, which are characteristic dynamometer records, the areas A', A'', etc., were found by a planimeter; by dividing any area thus found by the total length of its base between stops, the average height of the dynamometer records between stops is obtained. This average height when multiplied by the constant of the instrument, represents the average draw-bar pull between these stops.

(2) From passenger records taken during dynamometer tests, the curve shown in Fig. 15 was plotted, showing the ratio of the weight of the live load to the light weight of the train.

(3) Dividing the average pull in pounds by the total weight of the train, the average pounds per ton draw-bar pull over the run under consideration, was obtained. The average pounds per ton draw-bar pull thus obtained for each run is shown in Table I, page 637. The means of the values set forth in Table I are shown in Table II, page 638.

The average pounds per ton draw-bar pull (not tractive effort) for various lengths of run over the Mott Haven Division are shown in Curve 1, of Fig. 16. Curves 2 and 3 show these values for longer runs, as obtained on the Harlem and Hudson Divisions respectively, and Curve 4, which is the mean of Curves 1, 2 and 3, shows very roughly what may be expected to obtain as the average value of the "pounds per ton" draw-bar pull under ordinary steam railroad conditions, on a level and comparatively straight track, with various weights and lengths of train (three to ten cars, 100 to 400 tons), and at an average speed of about thirty miles per hour.

The question of grade is here eliminated, for each point shown represents the average value of two runs on the same train, one North, the other South.

The number of variables entering into these values such, for example, as the degree of skill of the engineer, the wind velocity, the condition of the track, agreement with schedule time, etc., make it impossible for any curve to pass through all its points and therefore, as above stated, these curves can only be taken as

TABLE I.

AVERAGE DRAW BAR PULL, IN POUNDS PER TON, FOR DIFFERENT RUNS ON N. Y. C. AND H. R. R. R.

Division, Key H., Hudson. A., Harlem.

Run.	† Out. + In.	Train.	Division.	Tons.	Pounds.	BETWEEN G. C. Station and 110 St	110 St. and 125 St.	G. C. Station and 125 St	125 St. and 138 St.	G. C. S. and 138 St.	138 St and Jct.	G. C. S. and Jct.	Jct and 125 St.
						3 42 M.	0.96 M.	4.38 M.	0.57 M	4.95 M.	0.85 M.	5.8 M.	.94 M.
19	+	120	H.	167.3	4 86				25.0				
"	"	"	"	"	2480			14.8					
22	†	111	H.	136 5	3080		22.3						
"	"	"	"	"	2240				16.4				
"	"	"	"	"	3620						26.5		
13	+	116	H.	126.4	1840						14.55		
"	"	"	"	"	2820				22.18				
"	"	"	"	"	1800			14.75					
18	†	113	H.	121.5	4000						32.9		
"	"	"	"	"	2800				22.1				
"	"	"	"	"	184			15.12					
52	†	115	H.	108 6	2180	20.05							
"	"	"	"	"	2880		26 5						
"	"	"	"	"	2820				25.9				
"	"	"	"	"	3880						30 2		
53	†	130	H.	103.1	4385						22.6		
"	"	"	"	"	4800				24 8				
"	"	"	"	"	5240		27.1						
"	"	"	"	"	2430	12.6							
55	+	153	H.	125.8	920						7.3		
"	"	"	"	"	3360				26.7				
"	"	"	"	"	3280		26						
"	"	"	"	"	1640	13.01							
12	†	111	H.	124.0	2300	18.6							
"	"	"	"	"	2780		22.4						
"	"	"	"	"	2600				21.0				
"	"	"	"	"	4020						32.4		
28	+	116	A	138.5					22.7				
"	"	"	"	"	3140								
"	"	"	"	"	1540			11.11					
49	+	28	A.	95					24.7				
"	"	"	"	"	2340								
"	"	"	"	"	1250			13.2				11.62	
41	+	88	H.	162.2	1884								
40	†	83	H.	231.3	3910			16.91					
"	"	"	"	"	3526				16.5				
"	"	"	"	"	6340						27.4		
39	+	84	H.	248.5	3500								14.2
"	"	"	"	"	2410			9.7					
38	†	87	H.	230.5	3015							13 03	
37	+	120	H.	177.6	2260								19.22
"	"	"	"	"	1436			12.21					
31	†	107	H.	143.8	2590			18 05					
"	"	"	"	"	3120								21.75
21	+	84	H.	267.8	4020								15.7
"	"	"	"	"	2925			10 92					
11	+	104	H.	223.8	3088							13.82	
16	†	103	H.	167.6	3132			18.65					
"	"	"	"	"	3110				18.6				
"	"	"	"	"	2960						17.7		
17	+	114	H.	176.1	4990								24.3
"	"	"	"	"	2984			16 95					
20	†	85	H.	230.	2410					10.46			
"	"	"	"	"	4980						21 7		
16	†	117	H.	195.	2890			14 8					
"	"	"	"	"	4040				21.5				
"	"	"	"	"	5050						25.9		
48	†	17	A.	137.3	1880	13.3							
"	"	"	"	"	2780		20.2						
"	"	"	"	"	2550				18.58				
"	"	"	"	"	4500						32.7		
14	†	11	A	193.4	2560			13.25					
"	"	"	"	"	2885				14.65				
"	"	"	"	"	4425						22.85		

TABLE I.—(*Continued.*)

AVERAGE DRAW BAR PULL, IN POUNDS PER TON, FOR DIFFERENT RUNS ON N. Y. C., AND H. R. R. R.

Division, Key. H., Hudson, A., Harlem.

Run.	+ Out. − In	Train.	Division.	Tons.	Pounds.	BETWEEN							
						G. C. Station and 110 St.	110 St. and 125 St.	G. C. S. and 125 St.	125 St. and 138 St	G. C. S and 138 St.	138 St. and Jct	G. C. S. and Jct.	Jct. and 135 St.
						3.42 M.	0.96 M.	4.38 M.	0.57 M.	4.95 M.	0.35 M.	5.3 M.	99 M.
15	+	24	A.	118.0	2725				23.05				
"		"	"	"	1495			12.7					
54	+	147	A.	213.2	3420	16.0							
"		"	"	"	4420		20.9						
"		"	"	"	3700				17 35				
"		"	"	"	5100						23.9		
7	+	28	H.	425.	3500						8.25		
"		"	"	"	7440				17 25				
"		"	"	"	5310			13.6					
42	+	94	H.	316.6	9660			11.56					
"		"	"	"	5000				18.8				
"		"	"	"	6410						20.25		
43	+	70	H.	195.3	2780								14.22
"		"	"	"	1890			9.68					
44	+	69	H	283.4	4150			14 66					
"		"	"	"	4790				16.9				
"		"	"	"	4920						17.37		
45	+	78	H.	142.7	2820								19.72
"		"	"	"	1365			9.66					
46	+	47	H	235 1	3075					13.06			
"		"	"	"	5680						24.21		
47	+	2	H.	307.	4785								15.6
"		"	"	"	3405			11.1					
50	+	71	H.	400.	4980			12.45					
"		"	"	"	3380								8.44
51	+	62	H.	302.1	5140								13.1
"		"	"	"	3900			9.95					
56	+	7	H	310.6	3890			12.52					
"		"	"	"	3200				10.3				
"		"	"	"	4840						15 58		

TABLE II.

SHOWING AVERAGE DRAW BAR PULL IN POUNDS PER TON, AND HORSE-POWER REQUIRED TO PROPEL ELECTRIC LOCOMOTIVES FOR DIFFERENT RUNS.

TERMINAL STATIONS Of run.	GOING OUT.		COMING IN.	
	2	3	4	5
1	Draw bar pull per ton	Locomotive h.p.	Draw bar pull per ton	Locomotive h.p.
Between G. C. Station and 110th Street.	17 lb	75. h.p.	12.80 lb.	71. h.p.
" " " " 125th "	16.13 "	88. "	13 10 "	65. "
" " " " 138th "	19.00 "			
" " " "Mott Haven Jc.	14.80 "	76. "	12.72 "	56. "
" 110th Street " 125th Street	22.46 "	95. "	24.00 "	98. "
" " " " 138th "				
" " " "Mott Haven Jc.			13.10 "	
" 138th " " 138th Street.	18.10 "	81. "	22.70 "	55. "
" " " "Mott Haven Jc.	16.00 "	73. "	17.00 "	58. "
" 138th " " " "	25.00 "	62. "	14.80 "	65. "

NOTE.—Figures given in columns 3 and 5 represent the average horse-power required to propel a 60 ton electric locomotive over that run, plus one horse-power for pumps.

TABLE III.

TABLE SHOWING DRAW BAR PULL, HORSE POWER REQUIRED, TRAIN WEIGHTS AND SCHEDULE SPEEDS, FOR TRAINS RUNNING BETWEEN MOTT HAVEN JUNCTION AND GRAND CENTRAL STATION ON THE N. Y. C. & H. R. R. R.—RESULTS OF DYNAMOMETER CAR TESTS.

H., Hudson Division. A., Harlem Division, N., N. Y. N. H. & H.

			G. C. S.				110.				125.				138.				Jct.
		Weight		Bet. G. C. S. and 110 St.				Bet. 110 St. and 125 Sts.				Bet. 125 St. and 138 Sts.				Bet. 138 St. and Jct.			
Division.	Train.	Light.	Loaded.	Schedule Speed.	Pounds per ton.	Pounds Total.	Horse Power	Schedule Speed.	Pounds per ton.	Pounds Total.	Horse Power.	Schedule Speed.	Pounds per ton.	Pounds Total.	Horse Power.	Schedule Speed.	Pounds per ton.	Pounds Total.	Horse Power.
N	2	308.9	324.0				+	32.8	16.13	5227.	458.				+	18.4	21.75	7050.	348.
N	4	249.0	261.0				+	32.8	16.13	4210.	370.				+	11.85	21.75	5680.	195.
N	200	194.26	198.75				+	29.2	16.13	3208.	252.				+	18.4	21.75	4330.	216.
H	41	369.8	388.29				+	29.2	16.13	6230.	482.	17.1	18.1	7026.	322.	13.8	25.0	9560.	352.
A	101	145.8	162.+	31.5	17.0	2752.	230.	23.0	22.46	3640.	225.	13.7	19.3	3130.	115.	10.3	25.36	4111.	113.
H	43	245.25	257.51				+	29.2	16.13	4125.	322.				+	18.4	16.	4120.	204.
H	32	324.45	341.	29.2	12.1	4122.	321.	+				15.8	17.	5800.	248.	+			
N	12	290.75	305.0				+	32.8	16.13	4920.	430.				+	18.45	21.75	6640.	330.
H	28	510.8	536.2	29.2	12.1	6500.	506.	+				13.68	22.7	12200.	445.	13.8	14.8	7940.	293.
N	69	305.3	320.5	29.2	12.88	4130.	323.	+				15.06	18.37	5890.	237.	+			
N	201	122.6	129.0	32.8	12.88	1662.	142.	+				18.4	18.37	2370.	116.	+			
A	152	114.96	126.45	25.6	12.80	1618.	110.	21.6	26.55	3350.	190.	12.83	23.3	2948.	102.	13.8	10.92	1380.	52.
N	203	243.26	250.56	29.2	12.88	3290.	255.	+				13.82	18.37	4700.	172.	+			
H	139	156.85	172.5				+	30.6	16.13	2780.	227.	12.84	19.3	3330.	114.	10.32	25.36	4380.	123.
A	151	89.38	100.+	30.8	17.00	1700.	142.5	21.6	22.46	2246.	130.	12.83	19.3	1930.	66.	10.34	25.36	2536.	71.
H	93	296.475	311.				+	30.3	16.13	4981.	400.	12.83	18.1	5632.	183.	10.3	25.0	7770.	214.
N	208	144.61	152.				+	+								29.18	13.03	1980.	155.
A	1	112.05	117.6				+	30.3	16.13	1895.	154.	12.83	19.3	2270.	77.5	10.32	25.36	2980.	83.
A	100	124.3	142.8	29.3	12.80	1828.	143.	21.6	26.55	3792.	218.	12.83	23.3	3330.	114.	12.4	10.92	1256.	42.
N	3	351.05	369.	37.5	12.88	4760.	480.	+				11.1	18.37	6780.	200.	+			
A	103	195.47	225.				+	30.3	16.13	3620.	293.	12.83	19.3	4340.	148.	10.3	25.36	5708.	160.
H	141	115.8	133.				+	30.3	16.13	2142.	174.	12.83	19.3	2565.	87.5	10.3	25.36	3370.	94.
N	209	107.25	125.5	29.2	12.88	1615.	126.	+				15.06	18.37	2305.	92.5	+			
A	102	121.69	137.5	29.3	12.80	1760.	140.	21.6	26.55	3650.	210.	12.85	23.3	3208.	110.	12.4	10.92	1502.	50.
N	5	315.42	331.0	29.2	12.88	4260.	332.	+				15.06	18.37	6080.	247.	+			
H	36	444.93	467.0	29.18	12.1	5650.	440.	+				17.09	22.7	10610.	482.	12.4	14.8	6918.	228.
N	212	170.89	179.2				+	32.8	16.13	2392.	205.				+	18.4	21.75	3900.	192.
H	102	162.75	184.5	29.18	12.88	2378.	190.	+				15.06	18.75	3460.	138.	+			
A	2	215.05	244.	29.18	12.88	3140.	245.	+				12.83	23.3	5690.	193.	27.5	10.92	2662.	197.
A	154	103.15	117.+	25.06	12.8	1497.	100.	21.6	26.55	3110.	253.	12.83	23.3	2726.	93.	12.4	10.92	1280.	43.
A	153	90.48	102.+	30.76	17.00	1734.	146.	21.6	22.46	2290.	133.	12.82	19.3	1910.	67.	10.3	25.36	2809.	74.
H	62	402.8	423.	29.18	12.1	5120.	400.	+				15.06	17.	7200.	290.	+			
N	235	182.77	192.	29.18	12.88	2470.	187.	+				18.4	18.37	3503.	173.	+			
N	222	292.15	307.				+	30.3	16.13	4958.	408.				+	18.4	21.75	6680.	330.
H	101	162.85	193.8				+	30.3	16.13	3120.	253.	11.4	19.3	3740.	129.	20.65	25.36	4856.	167.
H	30	269.75	283.	29.18	12.1	3420.	267.	+				15.06	17.0	4810.	194.	+			
H	211	158.25	166.1	29.18	12.88	2170.	170.	+				18.4	18.37	3050.	150.	+			
N	104	191.35	228.	29.18	12.88	2935.	227.	+				18.4	18.37	4190.	205.	+			
A	156	181.8	216.	26.25	12.88	2780.	195.	+				12.8	23.3	5040.	187.5	12.4	10.92	2360.	78.
N	215	137.6	144.52	28.19	12.88	1862.	145.	+				18.4	18.37	2658.	130.	+			
A	105	86.85	102.2				+	30.3	16.13	1646.	133.	12.83	19.3	1972.	67.	10½	25.36	2509.	70.
H	143	120.30	143.5				+	30.3	16.13	2311.	188.	12.83	19.3	2770.	95.	10½	25.36	3640.	101.
H	140	156.85	188.	26.25	12.88	2422.	173.	+				12.82	23.3	4382.	150.	12.4	10.92	2055.	69.
N	213	195.23	233.	29.18	12.88	3030.	236.	+				15.06	18.37	4280.	172.	+			
A	104	259.6	355.	29.18	12.88	4580.	378.	+				12.83	23.3	8280.	280.	12.4	10.92	3880.	129.
H	54	149.7	157.1	29.18	12.1	1900.	148.	+				15.06	17.	2672.	108.	+			
H	53	235.49	247.5	+				29.18	16.13	3960.	308.	+				18.4	16.	3960.	197.
H	46	383.075	402.	29.18	12.1	4869.	280.	+				15.06	17.	6835.	278.	+			
H	45	216.7	227				+	30.3	16.13	3630.	294.	12.83	18.1	4110.	140.	10.3	25.	5680.	158.
A	158	151.8	182.+	22.75	12.80	2330.	140.	21.6	26.55	4840.	300.	12.83	23.3	4240.	145.	12.4	10.92	1990.	55.
N	118	286.85	301.				+	31.	16.13	4858.	402.				+	15.81	21.75	6545.	279.
N	216	98.45	103.4				+	29.18	16.13	1669.	130.				+	18.4	21.75	2250.	116.5
H	145	120.2	144.				+	30.3	16.13	2320.	190.	12.83	19.3	2780.	95.	10.3	25.36	3651.	101.
H	3	121.68	146.				+	30.3	16.13	2350.	193.	17.09	19.3	2820.	128.	10.3	25.36	3710.	103.
H	217	198.43	237.	29.18	12.88	3050.	237.5	+				13.8	18.37	4360.	160.	+			
N	106	188.15	225.	29.18	12.88	2900.	224.	+				12.83	23.3	5250.	180.	20½	10.92	2458.	137.
N	223	193.92	203.5	29.18	12.88	2620.	203.	+				18.4	18.37	3740.	185.	+			
A	4	283.6	349.	26.25	12.88	4500.	315.	+				18.4	18.37	6418.	320.	+			
A	106	212.85	250.4	29.18	12.88	3222.	250.	+				12.83	23.3	5921.	200.	12.4	10.92	2775.	93.
H	82	233.3	278.	29.18	12.88	3580.	286.	+				17.09	23.3	6480.	296.	12.4	10.92	3035.	101.
N	221	215.78	250.7	29.18	12.88	3310.	259.	+				18.4	18.37	4735.	217.	+			
N	51	248.97	261.45				+								+	26.48	14.8	3870.	273.
N	227	220.17	231.3	29.18	12.88	2980.	232.	+				15.06	18.37	4260.	171.	+			
A	107	121.65	145.+	30.76	17.	2464.	250.	21.6	22.46	3255.	187.	12.83	19.3	2800.	96.	10½	25.36	3680.	104.
H	92	225.45	268.	29.18	12.88	3450.	267.	+				18.4	18.37	4920.	240.	+			
A	160	143.33	171.5	18.64	12.88	2197.	110.	21.6	26.55	4560.	262.	12.83	23.3	4000.	146.	12.4	10.92	1875.	63.
N	225	166.55	197.8	29.18	12.88	2505.	195.	+				18.4	18.37	3532.	175.	+			
H	142	115.8	137.5	29.18	12.88	1771.	135.	+				18.4	18.37	2503.	123.	+			
H	3	588.46	619.				+	30.3	16.13	9920.	803.	17.09	18.1	11200.	462.	10½	25.	15490.	435.
H	108	236.2	280.	29.18	12.88	3600.	280.	+				17.9	23.3	6523.	300.	20½	10.92	3050.	166.
H	103	116.2	138.	23.62	17.	2346.	148.				+	34.40	21.	2440.	229.	10½	25.36	3500.	97.
H	108	195.47	282.	29.18	12.88	3630.	283.	+				12.83	23.3	6579.	225.	12.4	10.92	3080.	103.
H	229	191.58	227.	29.18	12.88	2925.	227.5	+				18.4	18.37	4175.	208.	+			
N	218	135.33	142.2				+	30.3	16.13	2295.	184.				+	18.4	21.75	3138.	154.
N	220	Sept. Only					+	30.3							+	13.8			
A	6	176.5	209.	26.25	12.88	2691.	208.	+				20.7	18.37	3840.	213.	+			
H	110	185.05	219.	29.18	12.88	2340.	180.	+				20.7	18.37	4025.	223.	+			
N	224	100.67	105.8				+	26.25	16.13	1708.	122.				+	27.6	21.75	2302.	170.
H	147	115.8	137.				+	24.6	16.13	2208.	150.	12.83	19.3	2540.	87.	10½	25.36	3472.	96.
A	5	155.2	163.				+	30.3	16.13	2610.	212.	12.83	18.1	2950.	102.	10.33	25.	4075.	114.
A	231	198.51	208.6	29.18	12.88	2685.	207.	+				20.7	18.37	3335.	187.	+			
H	144	120.37	142.	29.18	12.88	1830.	140.	+				12.83	23.3	3310.	104.	12.4	10.92	1551.	52.
A	8	218.35	230.	29.18	12.1	2780.	218.	+				18.4	17.	3910.	192.	+			
H	239	166.26	174.6	29.18	12.88	2250.	175.	+				12.83	23.3	4050.	138.	20.66	10.92	1905.	105.
H	94	235.03	297.	29.18	12.88	3825.	296.	+				12.83	23.3	6920.	235.	20.66	10.92	3240.	179.
H	13	305.26	320.5				+	30.3	16.13	5137.	420.	12.83	18.1	5800.	197.	20.66	25.	8010.	444.

H	94	235.03	297.		29.18	12.88	3825.	296.	+					12.83	23.3	6920.	235.	20.66	10.92	3240.	179.
H	13	305.26	320.5					+	30.3	16.13	5137.	420.		12.83	18.1	5800.	197.	20.66	25.	8010.	444.
A	162	155.9	184. +		25.06	12.80	2357.	156.	34.56	26.55	4890.	458.		12.83	23.3	4293.	115.	12.4	10.92	2010.	67.
A	233	139.4	163.8		25.06	12.88	2110.	141.	+					18.4	18.37	3010.	148.	+			
N	243	145.65	153.		29.18	12.88	1970.	148.	+					20.7	18.37	2812.	151.	+			
H	12	440.875	463.		29.18	12.87	5920.	460.	+					12.83	23.3	10570.	746.	20½	10.92	5030.	309.8
A	109	89.23	104.8 +		30.76	17.	1780.	145.	21.6	22.46	2352.	136.		12.83	19.3	2022.	68.	10.33	25.36	2657.	73.
A	146	120.2	139.4		29.18	12.88	1795.	138.	+					17.09	23.3	3250.	148.	20.66	10.92	1520.	84.
H	63	Saratoga	Express.		+			+	30.3					11.4				20.66			
H	81	148.	171.5					+	30.3	16.3	2761.	223.		11.4	19.3	3320.	97.5	20.66	25.36	4350.	240.
N	237	133.5	140.2		26.25	12.88	1806.	126.	+					18.4	18.37	2508.	123.	+			
A	110	86.35	99.		29.18	12.88	1275.	97.	+					11.04	18.37	1819.	55.	+			
H	84	191.5	219.		29.18	12.88	2820.	218.	+					15.06	18.37	4025.	168.	+			
H	6	457.75	481.		29.18	12.1	5820.	452.	+					11.4	22.7	10920.	534.	20.66	14.8	7120.	395.
N	24	220.7	232.														+	31.8	13.03	3025.	258.
N	26	287.1	302.					+	30.3	16.13	4880.	400.					+	13.8	21.75	6570.	241.
N	245	159.17	167.3		26.25	12.88	2155.	152.	+					18.4	18.37	3071.	148.	+			
N	228	112.7	118.5					+	29.18	16.13	1910.	148.					+	18.4	21.75	2508.	123.
N	247	198.73	207.8		26.25	12.88	2672.	185.	+					18.4	18.37	3820.	189.	+			
A	10	157.7	178.		29.18	12.88	2292.	175.	+					12.83	23.3	4151.	140.	12.4	10.92	1945.	65.
H	112	162.85	184.		29.18	12.88	2370.	183.	+					20.52	23.3	4295.	235.	25.	10.92	2010.	135.
H	68	218.84	230.		32.8	12.88	2960.	257.5	+					11.4	23.3	5361.	178.	12.4	10.92	2501.	85.
H	7	253.85	303.					+	30.3	16.13	4860.	393.		12.83	18.1	5480.	188.	10.33	25.	7575.	209.
A	111	90.47	100.5 +		29.18	17.	1710.	133.9	21.6	22.46	2256	132.		12.83	19.3	1940.	67.	10.33	25.36	2505.	70.
A	105	114.65	126.					+	30.3	16.13	2019.	164.		11.4	19.3	2430.	83.	20.66	25.36	3192.	177.
A	112	121.65	133. +		29.25	12.80	1703.	135.	21.6	26.55	3503.	202.		12.83	23.3	3100.	107.	12.4	10.92	1454.	48.
N	253	158.77	167.		29.18	12.88	2150.	162.	+					18.4	18.37	3070.	148.	+			
N	232	220.1	232.2					+	29.18	16.13	3750.	292.					+	18.4	21.75	5060.	249.
N	234	184.56	198.					+	30.3	16.13	3192.	265.					+	13.8	21.75	4312.	160.
H	66	187.5	198.	29.18	12.1	2393.	187.	+						18.4	17.	3362.	164.	+			
N	251	171.55	180.2	29.18	12.88	2320.	181	+						18.4	18.37	3312.	163.	+			
A	155	123.1	133.9 +	30.76	17.	2275.	187.	21.6	22.46	2994.	173.			12.83	19.3	2508.	87.	10.33	25.36	3380.	94.
A	255	332.5	349.2	29.18	12.88	4500.	350.	+						13.8	18.37	6420.	238.	+			
A	14	183.975	193.	29.18	12.1	2332.	180.	+						20.52	22.7	4386.	245.	10.33	14.8	2855.	78.
H	47	264.4	278.					+	27.15	16.13	4470.	324.		34.18	18.1	5040.	459.	10.33	25.	6915.	192.
H	149	120.2	130.					+	30.3	16.13	2092.	170.		12.83	19.3	2501.	85.	10½	25.36	3300.	92.
A	44	89.23	96.75	29.25	12.80	1238.	97.	21.6	26.55	2504.	145.			12.83	23.3	2255.	78.	12.4	10.92	1057.	35.
H	148	115.8	125.8	29.18	12.88	1616.	125.	+						12.83	23.3	2924.	100.	12.4	10.92	1371.	47.
N	238	320.47	336.8					+									+	31.8	13.03	4390.	370.
N	240	136.91	144.					+	31.8	16.13	2320.	198.					+	18.4	21.75	3135.	152.
N	242	116.35	122.3					+	31.8	16.13	1973.	167.					+	18.4	21.75	2441.	120.
A	16	107.65	116.5	29.18	12.88	1500.	115.	+						12.83	23.3	2730.	93.	12.4	10.92	1274.	43.
A	83	149.3	161.5					+	30.3	16.13	2600.	213.		12.83	19.3	3115.	103.	10½	25.36	4100.	114.
A	157	86.35	93.4					+	30.3	16.13	1505.	123.		12.83	19.3	1800.	62.	10½	25.36	2370.	65.
N	261	125.6	132.	29.18	12.88	1700.	135.	+						18.4	18.37	2425.	125.	+			
A	113	88.95	96.3					+	30.3	16.13	1551.	126.		12.83	19.3	1857.	63.	20½	25.36	2440.	135.
H	116	116.2	126.	29.18	12.88	1624.5	126.	+						12.83	23.3	2935.	100.	31.	10.92	1377.	119.
N	265	174.65	183.5	29.18	12.88	2365.	187.	+						13.8	18.37	3370.	125.	+			
H	116	119.98	130.	29.18	12.88	1675.	130.	+						12.83	23.3	3030.	104.	12.4	10.92	1420.	47.5
H	70	174.35	183.	29.18	12.1	2313.	178.	+						15.06	17.	3112.	127.	+			
H	11	461.	485.					+	30.3	16.13	7765.	630.		11.4	18.1	8780.	268.	20½	25.	12130.	410.
N	106	149.15	156.7					+	37.5	16.13	2503.	253.					+	18.4	21.75	3410.	170.
N	36	251.07	264.					+	29.18	16.13	4260.	330.					+	18.4	21.75	5750.	285.
N	244	Saturday	Only					+	29.18								+	29.18			
H	107	120.2	130.2					+	30.3	16.13	2096.	170.		20.52	19.13	2501.	138.	20½	25.36	3300.	183.
N	246	101.17	106.2					+	29.18	16.13	1715.	133.					+	18.4	21.75	2311.	113.
N	138	Sunday	Only.																		
N	267	150.94	158.5	29.18	12.88	2040.	156.	+						18.4	18.37	2910.	147.5	+			
H	86	173.15	188.	29.18	12.88	2421.	187.	+						18.4	18.37	3450.	170.	+			
H	10	388.5	408.	29.18	12.1	4940.	383.	+						15.06	17.	6940.	283.	+			
A	115	115.2	125.					+	30.3	16.13	2016.	166.		17.01	19.3	2412.	109.	10½	25.36	3170.	87.5
A	164	115.48	125.2 +	29.25	17.0	2130.	165.	21.6	22.46	2810.	163.			12.83	19.3	2413.	83.	12.4	25.36	3172.	105.
A	118	119.2	129.4	29.18	12.88	1667.	128.	+						12.83	23.3	3015.	104.	12.4	10.92	1413.	45.
N	269	263.14	276.6	29.18	12.88	3560.	272.	+						18.4	18.37	5080.	250.	+			
N	119	379.12	398.8	29.18	12.88	5152.	400.	+						18.4	18.37	7322.	361.	+			
H	21	358.5	377.					+	30.3	16.13	6040.	490.		11.4	18.1	6825.	205.	20½	25.	9425.	520.
N	252	276.13	290.					+	29.18	16.13	4680.	365.					+	18.4	21.75	6305.	311.
N	256	141.3	148.5					+	29.18	16.13	2395.	238.					+	18.4	21.75	3230.	160.
H	97	191.35	201.					+	29.18	16.13	3240.	250.					+	18.4	21.75	4372.	218.
A	11	165.85	180.4					+	30.3	16.13	2908.	238.		12.83	19.3	3480.	119.	10½	25.36	4580.	128.
H	109	144.95	157.5					+	30.3	16.13	2504.	204.		12.83	19.3	3040.	104.	20½	25.36	4000	222.
H	150	120.15	120.5	29.18	12.88	1681.	129.							12.83	23.3	3040.	104.	12.4	10.92	1425.	48.
A	161	91.75	99.75	30.16	17.	1700.	140.	34.56	22.46	2239.	207.			12.83	19.3	1925.	53.	10.	25.36	2536.	68.
A	117	87.97	95.8					+	30.3	16.13	1543.	124.		12.83	19.3	1848.	63.	10½	25.36	2430.	68.
A	166	86.35	93. +	29.25	12.80	1192.	94.	21.6	26.55	1498.	88.			12.83	23.3	2167.	74.	12.4	10.92	1015.	33.
A	18	121.69	133.	29.18	12.88	1714.	132.	+						12.83	23.3	3100.	107.	12.4	10.92	1454.	48.
H	118	114.65	125.4	29.18	12.88	1615.	125.5	+						12.83	23.3	2928.	101.	12.4	10.92	1369.	47.
H	111	116.2	127.				+	30.3	16.13	20.48	168.			12.83	19.3	2450.	84.	10.5	25.36	3220.	89.
N	257	262.01	275.5	29.18	12.88	3505.	273.	+						13.8	18.37	5065.	188.	+			
A	7	142.3	154.4				+	30.3	16.13	2485.	202.			12.83	19.3	2979.	103.	10.33	25.36	3915.	108.
H	114	157.	170.	29.18	12.88	2190.	168.	+						18.4	18.37	3120.	153.	+			
H	16	201.	274.	32.8	12.1	3310.	268.	+						20.52	22.7	6220.	350.	7	14.8	4055.	77.
N	25	275.77	290.	29.18	12.88	3735.	290.	+						18.4	18.37	5331.	262.	+			
N	44	454.43	478.					+									+	31.8	13.03	6238.	527.
N	258	269.23	283.					+	29.18	16.13	4550.	355.					+	18.4	21.75	6150.	305.
N	260	134.62	147.5					+	29.18	16.13	2380.	236.					+	18.4	21.75	3210.	159.
A	168	123.12	135.	29.25	12.80	1728.5	134.5	21.6	26.55	3507.5	203.			12.83	23.3	3146.	108.	12.4	10.92	1475.	48.5
A	163	93.68	102.8 +	30.76	17.	1748.	143.	21.6	22.46	2310.	134.			12.83	19.3	1982.	68.	10.33	25.36	2610.	72.5
H	201	JunetoSept.					+	29.18						17.09				20.66			
H	72	209.85	220.	29.18	12.88	2832.	220.	+						20.52	23.3	5130.	282.	12.4	10.92	2403.	80.
H	273	376.65	396.	29.18	12.88	5100.	390.	+						13 8	18.37	7280.	269.	+			
H	67	187.5	197.				+	29.18	16.13	3155.	245.			17.09	18.1	3506.	160.	20.66	25.	4925.	273.
H	264	265.95	279.5				+	29.18	16.13	4510.	351.						+	18.4	21.75	6080.	300.
N	266	108.54	114.				+	29.18	16.13	1540.	145.						+	18.4	21.75	2480.	121.
A	119	94.05	103.6				+	30.3	16.13	1670.	136.			12.83	19.3	2000.	67.	20.66	25.36	2628.	148.
H	69	213.15	224.				+	30.3	16.13	3509.	289.			12.83	18.1	4050.	138.	10.33	25.	5600.	154.
A	15	187.975	196.5				+	30.3	16.13	3150.	255.			12.83	18.1	3555.	122.	20.66	25.	4920.	274.
H	151	162.85	180.				+	29.18	16.13	2900.	224.			12.83	19.3	3475.	118.	10.33	25.36	4570.	128.
A	165	86.45	95.8 +	30.76	17.	1630.	134.	21.6	22.46	2152.	168.			12.83	23.3	2549.	63.	10.33	25.36	2430.	68.
A	120	152.25	168.5	29.18	12.88	2170.	167.	+						12.83	23.3	3930.	133.	12.4	10.92	1841.	61.
H	120	116.2	128.8	29.18	12.88	1660.	129.5	+						12.83	23.3	3000.	103.	12.4	10.92	1407.	47.5
H	275	116.35	122.3	29.18	12.88	1575.	117.5	+						18.4	18.37	2248.	110.	+			
A	170	92.75	103. +	29.25	12.80	1319.5	102.	21.6	26.55	2735	158.			12.83	23.3	2400.	83.	12.4	10.92	1136.	37.5
H	17	345.5	353.				+	30.3	16.13	5660.	460.			11.4	18.1	6390.	195.	20.66	25.	8825.	488.
N	263	257.38	287.4				+										+	31.8	13.03	3745.	318.
N	270	217.1	228.2				+	29.18	16.13	3680.	287.						+	18.4	21.75	4973.	244.
A	17	92.6	102.8				+	29.18	16.13	1655.	130.			12.83	19.3	1985.	68.	20.66	25.36	2605.	149.
H	113	115.8	128.6				+	29.18	16.13	2071.	162.			11.4	19.3	2481.	76.	20.66	25.36	3261.	180.
N	272	163.3	171.6				+										+	31.4	13.03	2238.	197.
N	274	173.6	193.				+	29.18	16.13	3115.	242.						+	18.4	21.75	4200.	155.
A	167	90.7	101.5 +	30.72	17.	1725.	140.	21.6	22.46	2280.	132.			12.83	19.3	1960.	97.	10.33	25.36	2574.	72.
A	19	210.925	221.4				+	30.3	16.13	3504.	284.			12.83	18.1	4010.	137.	10.33	25.	5540.	155.
H	88	149.3	167.	32.8	12.88	2151.	188.	+						15.06	18.37	3068.	128.	+			
H	27	371.95	390.	29.18	12.88	5030.	391.	+						19.8	18.37	7170.	265.	+			
N	85	190.2	215.				+					+		27.8	10.46	2250.	167.	10.33	25.36	5460.	152.
N	278	167.34	176.				+	29.18	16.13	2840.	222.5	+					+	22.	21.75	3834.	228.
N	280	143.75	163.2				+	29.18	16.13	2632.	205.						+	18.4	21.75	3052.	150.
A	169	89.83	101.6 +	36.2	17.	1727.	177.5	21.6	22.46	2281.	132.			12.83	19.3	1960.	67.	10.33	25.36	2558.	70.
A	20	118.53	138.5	29.18	12.88	1636.	127.	+						12.83	23.3	2995.	102.	12.4	10.92	1403.	47.
A	155	114.6	124.				+	34.2	16.13	2127.	194.			20.52	19.3	2505.	138.	10.33	25.36	3245.	93.
H	99	227.7	240.				+	29.18	16.13	4250.	330.						+	18.4	21.75	5741.	283.
A	121	150.7	174.				+	29.18	16.13	2803.	218.			12.83	19.3	3360.	165.	17.6	25.36	4420.	268.

N	245	159.17	167.3	26.25	12.88	2155.	152.						18.4	18.37	3071.	148.							
N	228	112.7	118.5					29.18	16.13	1910.	148.						18.4	21.75	2508.	123.			
N	247	198.73	207.8	26.25	12.88	2672.	185.						18.4	18.37	3820.	189.							
A	10	157.7	178.	29.18	12.88	2292.	175.						12.83	23.3	4151.	140.	12.4	10.92	1945.	65.			
H	112	162.85	184.	29.18	12.88	2370.	183.						20.52	23.3	4295.	235.	25.	10.92	2010.	135.			
H	68	218.84	230.	32.8	12.88	2960.	257.5						11.4	23.3	5361.	178.	12.4	10.92	2501.	83.			
H	7	253.85	303.					30.3	16.13	4860.	393.		12.83	18.1	5480.	188.	10.33	25.	7575.	209.			
A	111	90 47	100.5+	29.18	17.	1710.	133.9	21.6	22.46	2256	132.		12.83	19.3	1940.	67.	10.33	25.36	2505.	70.			
A	105	114.65	126.					30.3	16.13	2019.	164.		11.4	19.3	2430.	83.	20.66	25.36	3192.	177.			
A	112	121.65	133. +	29.25	12.80	1703.	135.	21.6	26.55	3503.	202.		12.83	23.3	3100.	107.	12.4	10.92	1454.	48.			
A	253	158.77	167.	29.18	12.88	2150.	162.						18.4	18.37	3070.	148.							
N	232	220.1	232.2					29.18	16.13	3750.	292.						18.4	21.75	5060.	249.			
N	234	184.56	198.					30.3	16.13	3192.	265.						13.8	21.75	4312.	160.			
H	66	187.5	198.	29.18	12.1	2393.	187.						18.4	17.	3362.	164.							
H	251	171.55	180.2	29.18	12.88	2320.	181.						18.4	18.37	3312.	163.							
N	155	123.1	133.9+	30.76	17.	2275.	187.	21.6	22.46	2994.	173.		12.83	19.3	2508.	87.	10.33	25.36	3380.	94.			
A	255	332.5	349.2	29.18	12.88	4500.	350.						13.8	18.37	6420.	238.							
A	14	183.975	193.	29.18	12.1	2332.	180.						20.52	22.7	4386.	245.	10.33	14.8	2855.	78.			
A	47	264.4	278.					27.15	16.13	4470.	324.		34.18	18.1	5040.	459.	10.33	25.	6915.	192.			
H	149	120.2	130.					30.3	16.13	2092.	170.		12.83	19.3	2501.	85.	10+	25.36	3300.	92.			
A	44	89.23	96.75	29.25	12.80	1238.	97.	21.6	26.55	2504.	145.		12.83	23.3	2255.	78.	12.4	10.92	1057.	35.			
H	148	115.8	125.5	29.18	12.88	1616.	125.						12.83	23.3	2924.	100.	12.4	10.92	1371.	47.			
H	238	320.47	336.8														31.8	13.03	4390.	370.			
N	240	136.91	144.					31.8	16.13	2320.	198.						18.4	21.75	3135.	152.			
N	242	116.35	122.3					31.8	16.13	1973.	167.						18.4	21.75	2441.	120.			
A	16	107.65	116.5	29.18	12.88	1500.	115.						12.83	23.3	2730.	93.	12.4	10.92	1274.	43.			
H	83	149.3	161.5					30.3	16.13	2600.	213.		12.83	19.3	3115.	103.	10+	25.36	4100.	114.			
H	157	86.35	93.4					30.3	16.13	1505.	123.		12.83	19.3	1800.	62.	10+	25.36	2370.	65.			
A	261	125.6	132.	29.18	12.88	1700.	135.						18.4	18.37	2425.	125.							
N	113	88.95	96.3					30.3	16.13	1551.	126.		12.83	19.3	1857.	63.	20+	25.36	2440.	135.			
H	116	116.2	126.	29.18	12.88	1624.5	126.						12.83	23.3	2935.	100.	31.	10.92	1377.	119.			
H	265	174.65	183.5	29.18	12.88	2365.	187.						13.8	18.37	3370.	125.							
H	116	119.98	130.	29.18	12.88	1675.	130.						12.83	23.3	3030.	104.	12.4	10.92	1420.	47.5			
A	70	174.35	183.	29.18	12.1	2313.	178.						15.06	17.	3112.	127.							
H	11	461.	485.					30.3	16.13	7765.	630.		11.4	18.1	8780.	268.	20+	25.	12130.	410.			
N	106	149.15	156.7					37.5	16.13	2503.	253.						18.4	21.75	3410.	170.			
N	36	251.07	264.					29.18	16.13	4260.	330.						18.4	21.75	5750.	285.			
N	244	Saturday	Only					29.18									29.18						
N	107	120.2	130.2					30.3	16.13	2096.	170.		20.52	19.13	2501.	138.	20+	25.36	3300.	183.			
N	246	101.17	106.2					29.18	16.13	1715.	133.						18.4	21.75	2311.	113.			
H	138	Sunday	Only.																				
H	267	150.94	158.5	29.18	12.88	2040.	156.						18.4	18.37	2910.	147.5							
H	86	173.15	188.	29.18	12.88	2421.	187.						18.4	18.37	3450.	170.							
H	10	388.5	408.	29.18	12.1	4940.	383.						15.06	17.	6940.	283.							
A	115	115.2	125.					30.3	16.13	2016.	166.		17.01	19.3	2412.	100.	10+	25.36	3170.	87.5			
A	164	115.48	125.2+	29.25	17.0	2130.	165.	21.6	22.46	2810.	163.		12.83	19.3	2413.	83.	12.4	25.36	3172.	105.			
A	118	119.2	129.4	29.18	12.88	1667.	128.						12.83	23.3	3015.	104.	12.4	10.92	1413.	45.			
N	269	263.14	276.6	29.18	12.88	3560.	272.						18.4	18.37	5080.	250.							
N	119	379.12	398.8	29.18	12.88	5152.	400.						18.4	18.37	7322.	361.							
H	21	358.5	377.					30.3	16.13	6040.	490.		11.4	18.1	6825.	205.	20+	25.	9425.	520.			
N	252	276.13	290.					29.18	16.13	4680.	365.						18.4	21.75	6305.	311.			
N	256	141.3	148.5					29.18	16.13	2395.	238.						18.4	21.75	3230.	160.			
H	97	191.35	201.					29.18	16.13	3240.	250.						18.4	21.75	4372.	218.			
A	11	165.85	180.4					30.3	16.13	2908.	238.		12.83	19.3	3480.	119.	10+	25.36	4580.	128.			
A	109	144.95	157.5					30.3	16.13	2504.	204.		12.83	19.3	3040.	104.	20+	25.36	4000.	222.			
A	150	120.15	130.5	29.18	12.88	1681.	129.						12.83	23.3	3040.	104.	12.4	10.92	1425.	48.			
A	161	91.75	99.75	30.16	17.	1700.	140.	34.56	22.46	2239.	207.		10.	19.3	1925.	53.	10.	25.36	2536.	68.			
A	117	87.97	95.8					30.3	16.13	1543.	124.		12.83	19.3	1848.	63.	10+	25.36	2430.	68.			
A	166	86.35	93. +	29.25	12.80	1192.	94.	21.6	26.55	1498.	88.		12.83	23.3	2167.	74.	12.4	10.92	1015.	33.			
A	18	121.69	133.	29.18	12.88	1714.	132.						12.83	23.3	3100.	107.	12.4	10.92	1454.	48.			
H	118	114.65	125.4	29.18	12.88	1615.	125.5						12.83	23.3	2928.	101.	12.4	10.92	1369.	47.			
H	111	116.2	127.					30.3	16.13	20.48	168.		12.83	19.3	2450.	84.	10.5	25.36	3220.	89.			
N	257	262.01	275.5	29.18	12.88	3505.	273.						13.8	18.37	5065.	188.							
A	7	142.3	154.4					30.3	16.13	2485.	202.		12.83	19.3	2979.	103.	10.33	25.36	3915.	108.			
H	114	157.	170.	29.18	12.88	2190.	168.						18.4	18.37	3120.	153.							
H	16	201.	274.	32.8	12.1	3310.	268.						20.52	22.7	6220.	350.	7.	14.8	4055.	77.			
H	25	275.77	290.	29.18	12.88	3735.	290.						18.4	18.37	5331.	262.							
N	44	454.43	478.														31.8	13.03	6238.	527.			
N	258	269.23	283.					29.18	16.13	4550.	355.						18.4	21.75	6150.	305.			
N	260	134.62	147.5					29.18	16.13	2380.	236.						18.4	21.75	3210.	159.			
A	168	123.12	135.	29.25	12.80	1728.5	134.5	21.6	26.55	3507.5	203.		12.83	23.3	3146.	108.	12.4	10.92	1475.	48.5			
A	163	93.68	102.8+	30.70	17.	1748.	143.	21.6	22.46	2310.	134.		12.83	19.3	1982.	68.	10.33	25.36	2610.	72.5			
H	201	JunetoSept.						29.18					17.09				20.66						
H	72	209.85	220.	29.18	12.88	2832.	220.						20.52	23.3	5130.	282.	12.4	10.92	2403.	80.			
H	273	376.65	396.	29.18	12.88	5100.	390.						13 8	18.37	7280.	269.							
H	67	187.5	197.					29.18	16.13	3155.	245.		17.09	18.1	3506.	160.	20.66	25.	4925.	273.			
N	264	265.95	279.5					29.18	16.13	4510.	351.						18.4	21.75	6080.	300.			
N	266	108.54	114.					29.18	16.13	1840.	145.						18.4	21.75	2480.	121.			
A	119	94.05	103.6					30.3	16.13	1670.	136.		12.83	19.3	2000.	67.	20.66	25.36	2628.	148.			
H	69	213.15	224.					30.3	16.13	3509.	289.		12.83	18.1	4050.	138.	10.33	25.	5600.	154.			
A	15	187.975	196.5					30.3	16.13	3150.	255.		12.83	18.1	3555.	122.	20.66	25.	4920.	274.			
H	151	162.85	180.					29.18	16.13	2900.	224.		12.83	19.3	3475.	118.	10.33	25.36	4570.	128.			
A	165	86.45	95.8+	30.76	17.	1630.	134.	21.6	22.46	2152.	168.		12.83	19.3	1849.	63.	10.33	25.36	2430.	68.			
A	120	152.25	168.5	29.18	12.88	2170.	167.						12.83	23.3	3930.	133.	12.4	10.92	1841.	61.			
H	120	116.2	128.8	29.18	12.88	1660.	129.5						12.83	23.3	3000.	103.	12.4	10.92	1407.	47.5			
N	275	116.35	122.3	29.18	12.88	1575.	117.5						18.4	18.37	2248.	110.							
A	170	92.75	103. +	29.25	12.80	1319.5	102.	21.6	26.55	2735	158.		12.83	23.3	2400.	83.	12.4	10.92	1136.	37.5			
A	17	345.5	353.					30.3	16.13	5660.	460.		11.4	18.1	6390.	195.	20.66	25.	8825.	488.			
N	263	257.38	287.4														31.8	13.03	3745.	318.			
N	270	217.1	228.2					29.18	16.13	3680.	287.						18.4	21.75	4973.	244.			
A	17	92.6	102.8					29.18	16.13	1655.	130.		12.83	19.3	1985.	68.	20.66	25.36	2605.	149.			
H	113	115.8	128.6					29.18	16.13	2071.	162.		11.4	19.3	2481.	76.	20.66	25.36	3261.	180.			
N	272	163.3	171.6														31.4	13.03	2238.	197.			
N	274	173.6	193.					29.18	16.13	3115.	242.						13.8	21.75	4200.	155.			
A	167	90.7	101.5+	30.72	17.	1725.	140.	21.6	22.46	2280.	132.		12.83	19.3	1960.	97.	10.33	25.36	2574.	72.			
A	19	210.925	221.4					30.3	16.13	3504.	284.		12.83	18.1	4010.	137.	10.33	25.	5540.	155.			
A	88	149.3	167.	32.8	12.88	2151.	188.						15.06	18.37	3068.	128.							
H	27	371.95	390.	29.18	12.88	5030.	391.						13.8	18.37	7170.	265.							
H	85	190.2	215.									+	27.8	10.46	2250.	167.	10.33	25.36	5460.	152.			
N	278	167.34	176.					29.18	16.13	2840.	222.5						22.	21.75	3834.	228.			
N	280	143.75	163.2					29.18	16.33	2632.	205.						18.4	21.75	3052.	150.			
N	169	89.83	101.6+	36.2	17.	1727.	177.5	21.6	22.46	2281.	132.		12.83	19.3	1960.	67.	10.33	25.36	2568.	70.			
A	20	118.53	128.5	29.18	12.88	1656.	127.						12.83	23.3	2995.	102.	12.4	10.92	1403.	47.			
H	153	114.8	132.					34.2	16.13	2127	194.		20.52	19.3	2505.	138.	10.33	25.36	3345.	93.			
H	99	227.7	264.					29.18	16.13	4250.	330.						18.4	21.75	5741.	283.			
A	121	150.7	174.					29.18	16.13	2803.	218.		12.83	19.3	3360.	165.	17.6	25.36	4420.	209.			
H	122	120.22	139.	29.18	12.88	1790.	138.						12.83	23.3	3240.	111.	12.4	10.92	1520.	51.5			
N	279	116.4	122.2	29.18	12.88	1575.	122.5						12.4	18.37	2246.	75.							
N	52	412.6	434.					29.18	16.13	7000.	545.						18.4	21.75	9440.	467.			
N	284	111.85	117.5					29.18	16.13	1895.	147.						18.4	21.75	2505.	123.			
N	286	278.48	323.					29.18	16.13	5217.	405.						18.4	21.75	7030.	348.			
H	115	194.	224.					30.3	16.13	3610.	293.		11.4	19.3	4325.	130.	20.66	25.36	5680.	31.6			
A	171	118.	137. +	30.3	17.	2330.	190.	21.6	22.46	3074.	179.		12.83	19.3	2642.	90.	7.	25.36	3476.	65.			
A	172	93.68	108.6	29.25	12.80	1390.	107.	21.6	26.55	2381.	137.		12.83	23.3	2503.	85.	12.4	10.92	1186.	40.			
A	122	88.9	104.	29.18	12.88	1340.	104.						12.83	23.3	2423.	83.	12.4	10.92	1136.	38.			
H	155	120.37	141.					34.2	16.13	2270.	212.		20.52	19.3	2720.	149.	10.33	25.36	3508.	97.5			
H	152	162.35	186.	29.18	12.88	2398.	184.						12.83	23.3	4340.	147.	12.4	10.92	2032.	67.5			
A	21	223.4	261.					27.15	16.13	4208.	327.		34.18	19.3	5040.	460.	20.66	25.36	6620.	368.			
A	174	91.45	108.4+	29.25	12.80	3088.	106.	21.6	26.55	2376.	136.		12.83	23.3	2502.	85.	12.4	10.92	1184.	40.			
A	157	114.2	134.8					29.18	16.13	2171.	170.						18.4	21.75	2930.	144.			
A	123	157.56	186.					29.18	16.13	3000.	234.		12.83	19.3	3509.	120.	10.33	25.36	4720.	132.			
H	19	400.	420.					29.18	16.13	6730.	520.						18.4	16.	6722.	233.			
N	288	181.64	191.														31.8	13.03	2490.	213.			
N	290	220.17	231.5					29.18	16.13	3735.	275.						24.66	21.75	5040.	330.			
H	87	275.9	325.					29.18	16.13	5240.	406.						24.66	21.75	6850.	450.			
A	125	216.98	250.6					30.3	16.13	4040.	328.		20.52	19.3	4840.	270.	10.33	25.36	6490.	180.			

H	87	275.9	325.				+	29.18	16.13	5240.	406.							24.66	21.75	6850.	450.
A	125	216.98	250.6				+	30.3	16.13	4040.	328.	20.52	19.3	4840.	270.			10.33	25.36	6490.	180.
N	292	215.22	250.45				+	30.3	16.13	4105.	338.				+			24.66	21.75	5450.	358.
N	283	348.73	366.5	29.18	12.88	4725.	368.					18.4	18.37	6740.	333.						
H	117	162.4	192.2				+	30.3	16.13	3100.	252.	20.52	19.3	3710.	207.			10.33	25.36	4880.	134.
A	124	94.05	111.5	29.18	12.88	1436.	112.					12.83	23.3	2596.	88.			12.4	10.92	1219.	38.
N	281	135.4	142.2	29.18	12.88	1832.	142.5					20.7	18.37	2612.	145.						
A	173	169.1	200.5+	30.76	17.	3410.	280.	15.75	22.46	4505.	190.	12.83	19.3	3868.	132.			7.	25.36	5090.	94.
H	154	114.8	136.2	29.18	12.88	1755.	134.					20.52	23.3	3170.	174.			8.1	10.92	1487.	325.
H	291	165.39	173.6	29.18	12.88	2235.	173.					13.8	18.37	3190.	115.						
H	124	144.95	172.5	29.18	12.88	2222.	172.					12.83	23.3	4025.	137.			12.4	10.92	1885.	63.
N	107	208.8	219.2	29.18	12.85	2825.	220.					45.06	18.37	4030.	160.						
H	18	605.5	636.	29.18	12.1	7690.	600.					15.06	17.	10820.	435.						
A	176	93.7	119.5+	29.25	12.80	1530.	117.5	21.6	26.55	3171.	183.	12.83	23.3	2785.	95.			12.4	10.92	1306.	43.
H	23	309.435	325.				+	30.3	16.13	5210.	422.	12.83	18.1	5880.	199.			10.33	25.	8125.	225.
N	296	178.55	187.6												+			22.7	13.03	2442.	148.
N	294	292.97	307.2				+	30.3	16.13	4960.	408.	12.83	19.3	5940.	203.			10.33	25.36	7800.	236.
A	175	220.53	262.5+	30.75	17.	4465.	365.	15.75	22.46	5900.	248.	12.83	19.3	5065.	170.			10.33	25.36	6658.	184.
H	119	233.55	281.				+	29.18	16.13	4540.	350.				+			18.4	21.75	6110.	300.
N	298	266.52	317.8				+	30.3	16.13	5125.	420.				+			18.4	21.75	6910.	342.
A	23	171.8	205.				+	30.3	16.13	3800.	307.	17.09	19.3	3959.	181.			10.33	25.36	5200.	143.
A	22	100.7	128.	29.18	12.88	1650.	127.					18.4	18.37	2350.	115.						
H	156	120.37	143.6	29.18	12.88	1850.	144.					12.83	23.3	3345.	114.			12.4	10.92	1570.	52.
H	159	162.85	194.5				+	29.18	16.13	3131.	244.	12.83	19.3	3750.	128.			10.33	25.36	4940.	140.
A	127	210.8+	250.2+	23.62	17.	4260.	267.	34.56	22.46	5620.	325.				+			27.6	21.75	5480.	403.
H	56	163.2	171.4	29.18	12.88	2208.	172.					12.83	23.3	4000.	138.			12.4	10.92	1874.	63.
A	177	224.7	269.3	27.91	17.	4580.	340.	21.6	22.46	6042.	346.	12.83	19.3	5200.	178.			7.	25.36	6826.	128.
H	55	311.88	326.				+	30.3	16.13	5225.	425.	11.4	18.1	5900.	180.			20.66	25.	8150.	452.
H	22	339.75	356.	29.18	12.1	4308.	334.					18.4	17.	6060.	300.						
A	178	89.83	108. +	34.15	12.80	1383.	128.	21.6	26.55	2870.	165.	20.52	23.3	2502.	138.			8.11	10.92	1180.	27.
N	302	142.47	149.5												+			31.8	13.03	1950.	167.
N	304	196.7	235.2				+	29.18	16.13	3800.	296.				+			18.4	21.75	5128.	253.
H	71	338.75	355.				+	23.62	16.13	5720.	360.							13.8	16.	5680.	247.
A	129	163.45	195.				+	23.62	16.13	3160.	200.	13.8	19.3	3780.	129.			20.66	25.36	6978.	274.
A	128	123.77	145.5	29.18	12.88	1875.	144.					12.83	23.3	3390.	116.			12.4	10.92	1590.	55.
H	121	154.65	184.8				+	29.18	16.13	3036.	237.	20.52	19.3	3507.	193.			10.33	25.36	4780.	134.
A	179	217.85	260. +	30.76	17.	4430.	365.	15.75	22.46	5840.	470.	12.83	19.3	5020.	168.			10.33	25.36	6590.	183.
H	126	87.95	260.	29.18	12.88	3348.	263.					15.06	18.37	4780.	190.						
N	289	113.4	117.	26.25	12.88	1505.	106.					18.4	18.37	2150.	105.						
H	126	116.7	139.2	29.18	12.88	1795.	138.					15.06	18.37	2506.	100.						
H	2	283.425	297.5	26.25	12.1	3595.	255.					20.07	17.	5060.	273.						
N	306	130.33	137.					30.3	16.13	2210.	180.				+			13.8	21.75	2980.	110.
N	301	215.21	250.7	29.18	12.88	3310.	260.					24.66	18.37	4720.	311.						
N	123	114.8	137.				+	30.3	16.13	2209.	179.							13.8	21.75	2980.	110.
A	25	93.7	111.5				+	30.3	16.13	1800.	147.	17.09	19.3	2150.	98.			10.33	25.36	2325.	64.
H	158	114.2	136.5	29.18	12.88	1758.	136.					12.83	23.3	3180.	109.			12.4	10.92	1491.	50.
A	181	89.83	107. +	30.76	17.	1712.5	140.	34.4	22.46	2400.	222.	20.52	19.3	2065.	115.			7.	25.36	2711.	52.
A	24	100.08	119.	29.18	12.88	1533.	117.					15.06	23.3	2771.	115.			12.4	10.92	1260.	43.
H	29	480.7	505.				+	30.3	16.13	8100.	658.				+			13.8	16.	8080.	295.
A	180	118.03	140. +	29.18	12.80	1792.5	138.	29.18	26.55	3720.	290.	15.06	23.3	3260.	136.			12.8	10.92	1530.	50.5
H	125	114.65	155.8				+	30.3	16.13	2190.	179.	11.4	19.3	2620.	80.			20.66	25.36	3441.	167.5
A	131	87.95	104.2				+	30.3	16.13	1680.	137.	9.3	19.3	2010.	50.			20.66	25.36	2640.	145.
N	297	111.12	116.7	29.18	12.88	1504.	117.					24.66	18.37	2142.	141.						
H	128	115.8	136.8	29.18	12.88	1764.	117.5					12.83	23.3	3190.	109.			26.	10.92	1445.	100.
H	160	162.85	193.6	29.18	12.88	2492.	191.					12.83	23.3	4520.	155.			20.66	10.92	2115.	117.
N	37	424.62	446.	29.18	12.85	5750.	449.					15.06	18.37	8200.	351.						
N	305	135.37	142.	29.18	12.88	1830.	150.					15.06	18.37	2610.	105.						
N	310	134.7	141.6				+	30.3	16.13	2386.	195.				+			13.8	21.75	3080.	112.
N	312	109.19	114.8				+	29.18	16.13	1850.	144.				+			18.4	21.75	2475.	122.
A	133	89.4	103.3+	30.76	17.	1755.	144.	21.6	22.46	2319.	133.	12.83	19.3	1993.	67.			10.33	25.36	2620.	73.
A	182	155.58	179.8 +	27.9	12.8	2300.	170.	21.6	26.55	4780.	300.	12.83	23.3	4196.	144.			12.4	10.92	1965.	67.
N	299	To Sept.	Only.	29.18								15.06									
N	31	262.25	275.								+	29.65	12.	3300.	260.			10.33	25.	6875.	190.
H	303	192.94	203.	29.18	12.88	2615.	203.					18.4	18.37	3730.	185.						
A	26	157.75	165.7	29.18	12.1	2050.	160.					20.52	22.7	3764.	206.			10.33	14.8	2452.	68.
H	127	158.75	179.				+	29.18	16.13	2885.	225.	20.52	19.3	3455.	190.			10.33	25.36	4541.	126.
H	14	393.7	414.	30.3	12.1	5080.	412.					20.52	22.7	9400.	520.			7.	14.8	6130.	114.
A	183	100.07	111.3+	30.75	17.	1875.	153.	21.6	22.46	2500.	145.	20.52	19.3	2146.	118.			10.33	25.36	2320.	64.
A	307	196.84	218.2	23.85	12.88	2310.	147.5					18.4	18.37	4016.	198.5						
A	130	91.45	101.3	29.18	12.88	1304.	103.					12.83	23.3	2360.	81.			12.4	10.92	1106.	33.
A	45	376.57	395.5	29.18	12.88	5085.	396.					15.06	18.37	7250.	292.						
A	27	117.2	128.				+	30.3	16.13	2062.	167.	12.83	19.3	2470.	84.			10.33	25.36	3245.	90.
H	130	120.2	129.6	29.18	12.88	1670.	130.					12.83	23.3	3020.	103.			12.4	10.92	1416.	47.5
H	35	285.53	300.				+	29.18	16.13	4839.	380.							18.4	16.	4800.	238.
H	78	124.10	130.	26.25	12.88	1675.	123.					20.52	23.3	3030.	166.			20.66	10.92	1420.	78.
H	33	389.3	409.				+	30.3	16.13	6600.	536.				+			13.8	16.	6554.	240.
H	76	Sarat. Spec.	Jn.-Sept.	29.18	12.1							15.06	17.								
H	37	396.35	417.				+	30.3	16.13	6720.	544.	12.83	18.1	7540.	257.			8.11	25.	10430.	225.
N	316	242.14	250.5				+	30.3	16.13	4117.	338.				+			13.	21.75	5455.	190.
H	129	114.7	123.3					30.3	16.13	1986.	162.	11.4	19.3	2379.	73.			20.66	25.36	3125.	173.
A	28	104.3	111.5	29.18	12.88	1436.	110.					12.83	23.3	2600.	88.			12.4	10.92	1218.	42.
N	309	173.95	182.7	29.18	12.88	2355.	178.					18.4	18.37	3360.	166.						
H	132	114.8	123.1	24.45	12.72	1565.	104.														
H	50	244.65	257.	26.48	12.72	3268.	230.														
N	313	305.1	320.8	29.18	12.88	4220.	330.														
A	135	124.18	134. +	30.76	17.	2278.	186.	21.6	22.46	3010.	173.	18.4	18.37	5893.	291.						
A	184	89.82	95.4 +	29.25	12.80	1221.	95.	21.6	26.55	2503.	145.	12.83	19.3	2509.	87.			10.33	25.36	3400.	94.
H	52	298.8	314.	26.25	12.1	3800.	267.					12.83	23.3	2222.	77.			12.4	10.92	1042.	35.
H	319	86.66	91.	29.18	12.88	1172.	96.					20.7	17.	5340.	296.						
H	318	130.39	146.5				+	32.8	16.13	2362.	207.	18.4	18.37	1682.	88.						
H	131	120.2	126.				+	30.3	16.13	2030.	165.				+			18.4	21.75	3190.	156.8
A	132	87.95	91.85+	29.25	12.80	1176.	91.	21.6	26.55	2440.	142.	12.83	19.3	2430.	83.			20.66	25.36	3185.	175.
N	53	93.89	98.6	29.18	12.88	1257.	97.5					12.83	23.3	2140.	73.			12.4	10.92	1004.	34.
N	68	299.92	315.				+	29.18	16.13	5080.	395.	15.06	18.37	1812.	52.						
H	134	114.65	119.1	29.18	12.88	1534.	120.								+			18.4	21.75	6850.	338.
H	320	319.44	376.				+	29.18	16.13	6070.	470.	20.52	23.3	2775.	153.			12.4	10.92	1302.	46.
A	185	91.45	104. +	30.76	17.	1708	140.	21.6	22.46	3333.	135.	20.52	19.3	2010.	110.			13.8	21.75	8180.	301.
N	324	105.35	110.6				+	34.2	16.13	1785.	163.							7.	25.36	2038.	90.
A	29	120.05	123.6				+	30.3	16.13	1992.	162.	17.09	19.3	2385.	114.			18.4	21.75	2410.	118.
H	133	158.2	162.4				+	30.3	16.13	2616.	213.	11.4	19.3	3130.	95.			10.33	25.36	3132.	86.
H	180	289.65	303.	26.25	12.1	3665.	257.					20.52	22.7	6880.	380.			20.66	25.36	4120.	228.
A	134	89.4	91.3	29.18	12.88	1176.	92.					12.83	23.3	2125.	73.			12.4	14.8	4490.	148.
N	325	219.	230.	29.18	12.88	2962.	230.					18.4	18.37	4230.	210.			12.4	10.92	998.	34.

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indicating the average value of a widely varying quantity.

(4) Fig. 17 shows a graphical method of obtaining the speed in miles per hour between any two stations when the time of run between these two stations is given. If the lower strip of this diagram be cut off along the dotted line and placed horizontally at the left with any station on the ordinate at the given time, the intersection of any other station with an oblique line gives the average speed between these stations. Thus, for example,

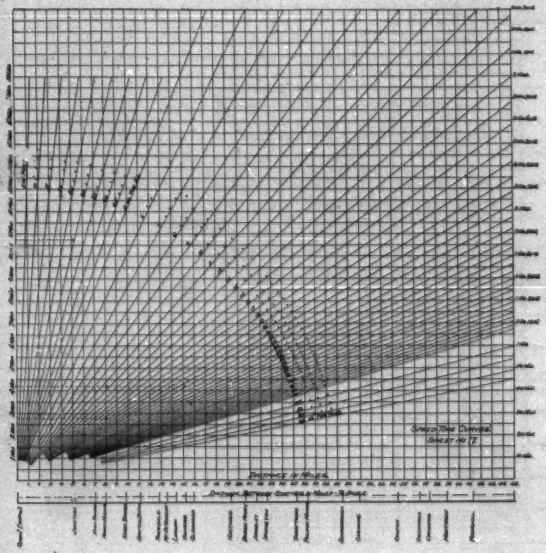

FIG. 17.

if the run from Grand Central Station to Yonkers is made in 42 minutes, by placing "Grand Central Station" on the ordinate at the left at 42 minutes and running horizontally along the strip to "Yonkers," the oblique line here intersected shows the average speed to be 22 miles per hour; in the same manner, if the run from Grand Central Station to Mott Haven Junction is made in 10½ minutes, the average speed is thirty miles per hour. Again, by placing "Spuyten Duyvil" on the ordinate at the left at 28 minutes, and following horizontally to "Hastings,"

the average speed between these two stations is seen to be 18 miles per hour.

(5) The weight of every train arriving or leaving the Grand Central Station on a given day was obtained, and its average speed between stops determined from the above curves. Knowing, therefore, the average draw-bar pull in pounds required to haul a train, and the average speed at which this draw-bar pull

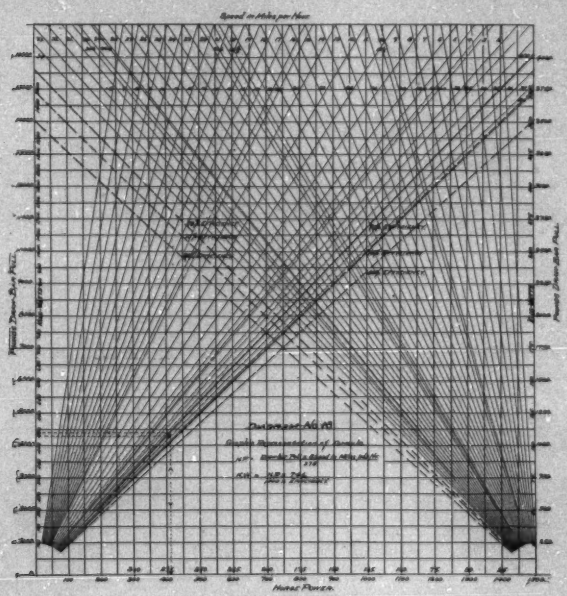

FIG. 18

was exerted, the horse power at the draw-bar becomes:

H.P. = foot pounds per minute/33,000
= draw-bar pull × miles per hour × 5,280/33,000 × 60
= draw-bar pull × miles per hour/375

This formula is represented graphically in Fig. 18, from which, knowing the draw-bar pull and speed, the horse power or kilowatts corresponding thereto is determined. Thus, for example, if the draw-bar pull is 4,300 lbs., at a speed of 36 miles per hour,

to find the horse power or kilowatts corresponding thereto. At 4,300 lbs., on the ordinate at the left of the figure, follow the dotted line to the right until it intersects the required speed curve, thence downward to the base line thus obtaining 410 horse power. If the efficiency of the motor is taken at 70%, by following the ordinate at 410 horse power vertically to the 70% curve and thence to the left, the kilowatt capacity required is found to be 440 k.w., which is the power required to propel the train, exclusive of the locomotive and head-end resistance.

Now, referring to the first line of Table 3, which represents the results obtained by calculating the power required for the train service of Oct. 23, 1901, we have for the first train shown:

In Column 1, the division over which the train runs, namely "N" (N. Y., N. H. &. H.)

In Column 2, the train number.

In Column 3, light weight of train.

In Column 4, weight of train loaded, which was obtained by reference to the curve in Fig. 15, showing the weight of passengers to be added to the light train weight.

The first stop being at 125th Street, Columns 5, 6, 7 and 8 are blank, but show by daggere the direction of movement, thus ⊣ North, ⊢ South.

In Column 9, is found the average speed obtained as above.

In Column 10, the pounds draw-bar pull from Table 2.

In Column 11, the product of "pounds per ton," times total tonnage of train

In Column 12, the average horse power required to haul a train, exclusive of the locomotive, from Grand Central Station to 125th Street; this value was obtained from Fig. 18, and is:

$$5{,}227 \times 32.8/475 = 458 \text{ horse power.}$$

No stop being made at 138th Street, Columns 13, 14, 15 and 16 are blank.

In Column 17, the average speed from 125th Street to Junction is found as above.

In Column 18, average pounds per ton draw-bar pull over this run.

In Column 19, the average total draw-bar pull.

In Column 20, the average horse power required at the draw-bar over this run.

The horse power required for each scheduled train over each run was obtained in the same manner and the results as taken from this table were plotted and are shown on train diagram sheets, Figs. 19, 20, 21 and 22.

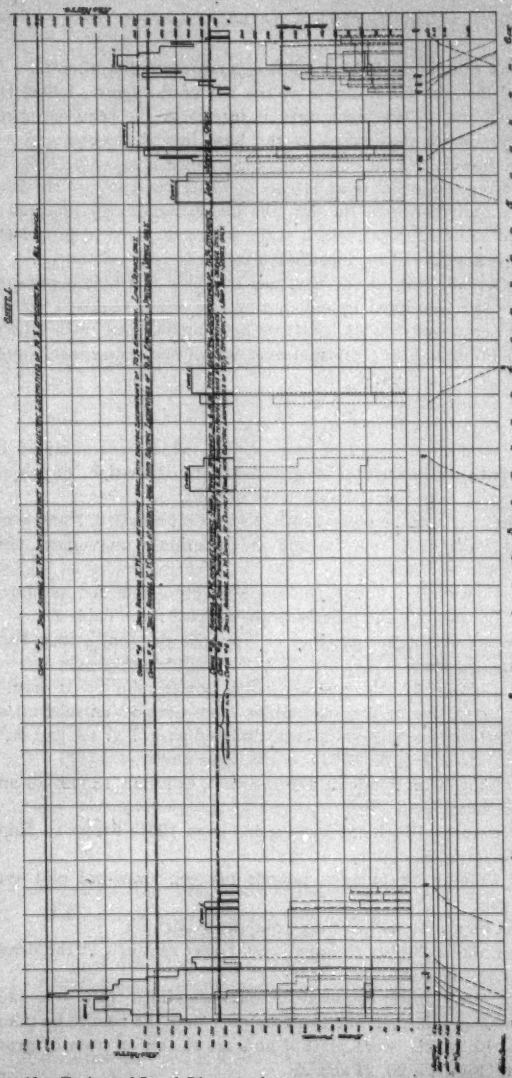

FIG. 19.—Train and Load Diagram for Oct. 23, 1901, showing energy required for proposed electric locomotive service between Grand Central Station and Mott Haven Junction, from 12 o'clock midnight to six o'clock A. M.

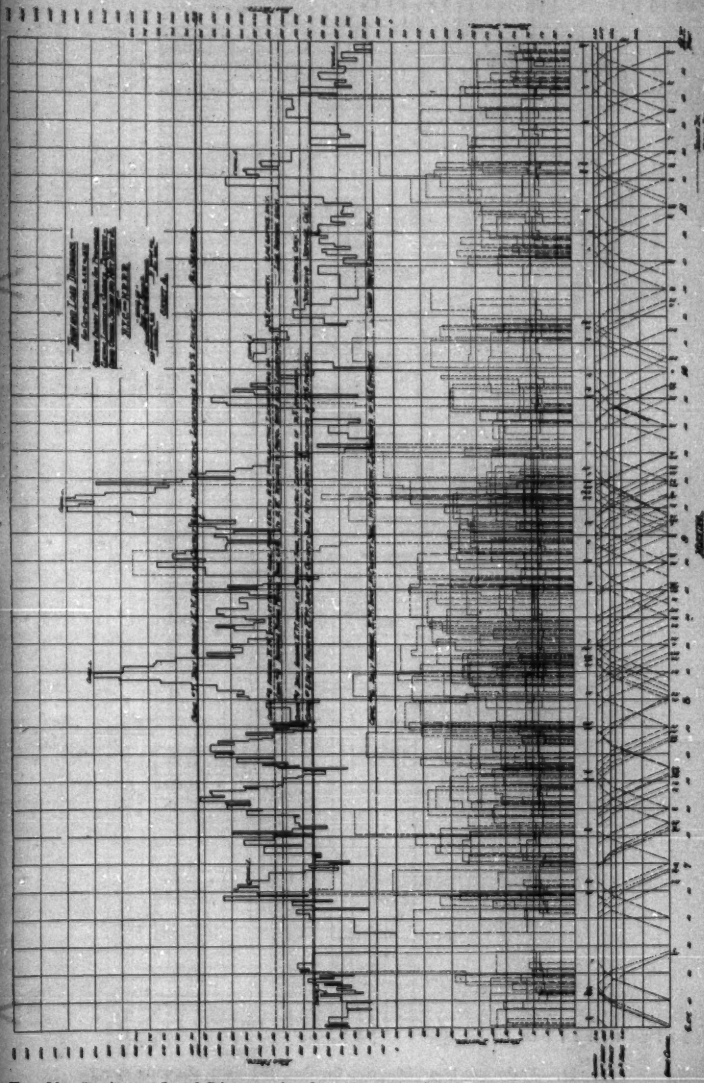

FIG. 20.—Train and Load Diagram for Oct 23, 1901, showing energy required for proposed electric locomotive service between Grand Central Station and Mott Haven Junction, from six o'clock A.M. to 12 o'clock noon.

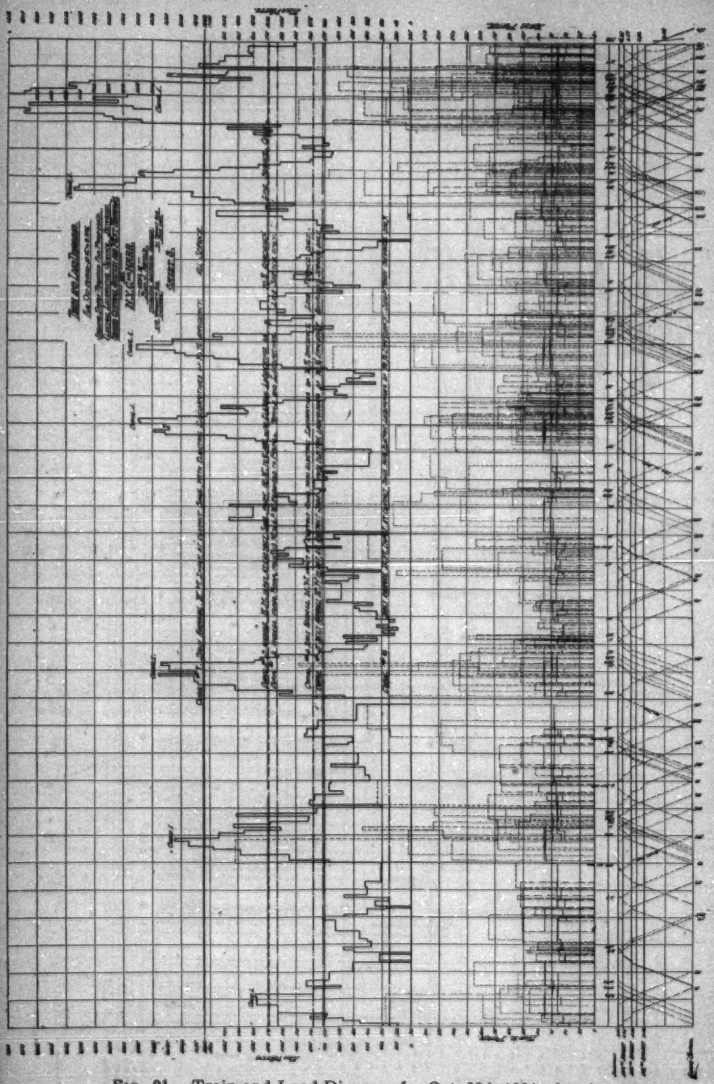

FIG. 21.—Train and Load Diagram for Oct. 23d, 1901, showing energy required for proposed electric locomotive service between Grand Central Station and Mott Haven Junction, from 12 o'clock noon to 6 P.M.

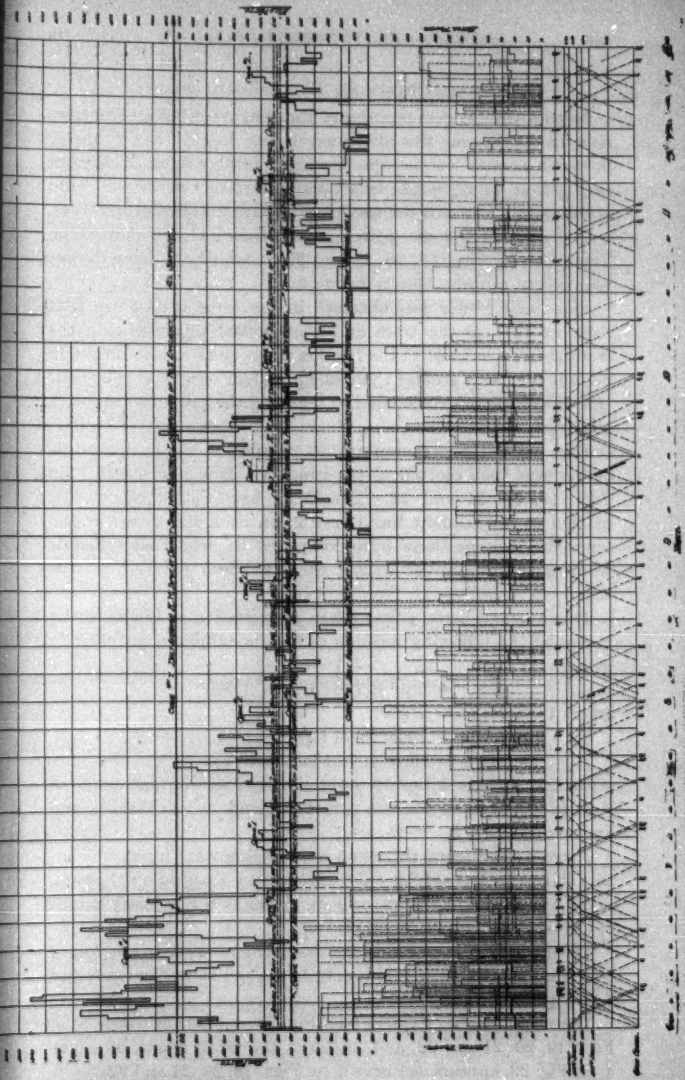

FIG. 22.—Train and Load Diagrams for Oct. 25th, 1901, showing energy required for proposed electric locomotive service between Grand Central Station and Mott Haven Junction, from 6 o'clock P.M. to 12 o'clock midnight.

METHOD OF OBTAINING DAILY LOAD DIAGRAM.

From a careful examination of the weights of all locomotives now in service on this division, it was found that properly powered electric locomotives having a total weight of 65 tons each, all of which would be available for tractive effort, could satisfactorily perform the service of existing steam locomotives.

To each train horse power curve, therefore, as plotted on Train Sheets, Figs. 19, 20, 21 and 22, is added the horse power required to propel a 65-ton locomotive.

This horse power was obtained in the same manner as that required to haul the train and was plotted separately on the train sheets; evidently, the friction of an electric locomotive in pounds per ton is greater than an equivalent weight of train, but this difference was considered in selecting the proper locomotive efficiency.

The sum of the instantaneous values of these individual curves was then plotted as the irregular black line Curve 1, in Figs. 19, 20, 21 and 22. The mean height of this curve is plotted as the straight line Curve 2, on each sheet, and represents the average horse power required to propel all schedule trains and locomotives during the six hours covered by the sheet.

This average horse power when converted into kilowatts by means of the following formula (which is exhibited graphically in Fig. 18):

$$\text{k.w.} = \text{h.p.} \times 746/70\% \times 1{,}000$$

where 1,000 watts = 1 k.w.

746 watts = 1 electrical h.p.

and 70% = efficiency of locomotives

gives the average kilowatt input required at contact shoes of electric locomotives for the period covered by each sheet and appears as Curve 3.

Curve 4 represents the mean average kilowatt input at contact shoes (for line service only) throughout a period of 24 hours, under the same conditions, and its height is the average height of Curve 3, in Figs, 19, 20, 21 and 22.

The switching, shop train and return engine service was found to represent such hourly demands as are shown in Curves 3 and 4 of Fig. 23.

The mean height of Curve 3 on Fig. 23, appears as Curve 5, in Figs. 19, 20, 21 and 22, and similarly, the mean height of Curve 4, on Fig. 23, appears as Curve 6, on Figs. 19, 20, 21 and 22.

The sum of Curves 4, 5, and 6 on Sheets 19, 20, 21 and 22, is plotted as Curve 7, on those sheets, and therefore represents the AVERAGE DAILY KILOWATT INPUT REQUIRED AT CONTACT SHOES OF LOCOMOTIVE FOR ALL SERVICE.

Curve 1 of Fig. 23, is a condensed load diagram of the entire service, showing the hourly variation of the different classes of service, as deduced from the curves in Figs. 19, 20, 21 and 22.

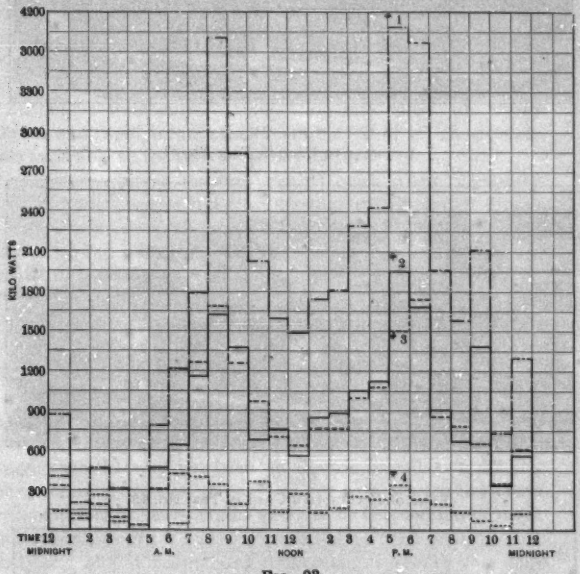

FIG. 23

From Curve 7, on these sheets, it is seen that the daily average input required would be at the rate of 1,800 kilowatts and, therefore, the total annual input required at the contact shoes of the locomotives, for propulsion alone, would be (1,800 × 24 × 365) = 15,768,000 k.w. hour). From the total number of tons hauled yearly over this division, including passenger, shop trains and switching service, the ton-miles per year were found to be 250,285,710. Hence, the electrical energy required to haul a ton one mile over this division under the existing conditions would be

FIG. 24
Locomotive Used in Test No. 27.

FIG. 25
Type of Locomotive Used in Test No. 48.

FIG. 26
Type of Locomotive Used in Test No. 22.

15,768,000,000/250,285,710 = 63 watt hours per ton-mile.

With this figure as a basis and the load factor as determined from the load diagram, the problem of determining the best method of producing, distributing and applying the power was considered.

Choice of System.

While it is the writer's opinion that the alternating current railway motor will yet prove to be the most efficient, all things considered, for long-distance railway work, it has not yet in his opinion demonstrated its ability to start under load as efficiently or to accelerate a train as rapidly as the direct current motor. The line under immediate consideration was short, the trains numerous and rapid acceleration desirable, all of which are conditions favorable to the direct current motor.

Furthermore, direct current motors with their necessary auxiliaries have become fairly well standardized and it is the only class of electric railway apparatus available from the manufacturers of the United States without involving experimental work and large development expense.

In view of these facts and the probable necessity for rapid construction, the writer refrained from advising anything of an experimental nature and, therefore, recommended the direct current system in combination with the third rail for the main line, and overhead construction for the yards, all of which have demonstrated fully their ability to meet the conditions imposed by railway operation so far as motive power is concerned, although there has not yet been an electric installation on any existing terminal that is as complex, or into which anywhere near the number of heavy trains enter, as on this section of road.

Had the length of road under consideration been considerably greater, and had it been thought possible to secure sufficient time to conduct experiments or invite demonstrations by manufacturers of alternating current motor equipment, this class of apparatus would have been more seriously considered.

Discussions and Analysis of Plans and Estimates.

In the preparation of estimates, twelve distinct plans of generation and distribution were considered and the results tabulated as shown in Table 4. All the estimates were computed upon the same basis so far as cost of fuel, labor and losses in transmission were concerned. The different headings in the table here shown are deduced from another table not here published, the columns of which were as follows:

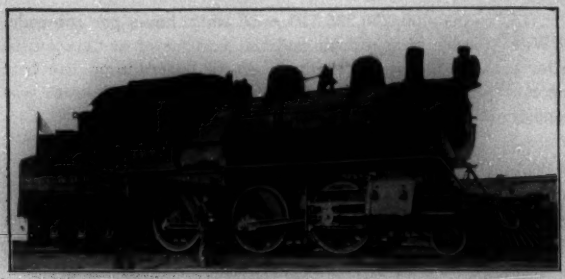

FIG. 27
Locomotive Used in Test No. 53.

FIG. 28
Type of Locomotive Used in Test No. 7.

FIG. 29
Type of Locomotive Used in Test No. 56.

Column A.—*Total Cost of Entire Installation.*—Erected complete, consisting of power-house, transmission circuits, feeders, sub-stations, track construction chargeable to electrical equipment, overhead construction and electric locomotives.

Column B.—*Total Operating Expenses per Annum.*—Including wages in power-house and sub-stations and on rolling stock, together with all coal, oil, water, waste, repairs, etc.

Column C.—*Fixed Charges per Annum.*—Including interest at 4% on total investment, and taxes at 2% on buildings, sites, machinery and electric locomotives.

Column D.—*Total Expense per Annum.*—Made up of Column B plus Column C.

Column E.—*Operating Expenses per Annum at Power-House.*

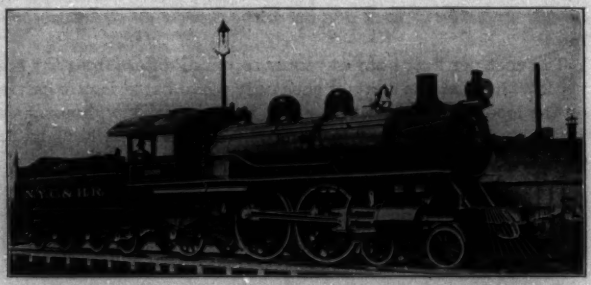

FIG. 80.
Type of Locomotive Used in Test No 6.

—Including coal, water, oil, waste, etc., and repairs and wages.

Column F.—*Operating Expenses per Annum at Contact Shoe.*—Including coal, water, oil, waste, etc., and repairs and wages in power-house; oil, waste, repairs and wages in sub-stations; and repairs (labor and material) on transmission lines.

Column G.—*Total Expense per Annum Exclusive of Rolling Stock.*—Including operating expenses per annum at contact shoe (as in preceding Column F) plus fixed charges as follows: interest at 4% on total investment (less cost of electric locomotives) and taxes at 2% on buildings, sites and machinery.

Column I.—*Total Locomotive Miles per Annum.*—Determined from information furnished through the Operating Department.

The explanation of the columns in Table 4, page 653, is as follows:

Column H is

$$\frac{\text{Column E (of table not published)}}{\text{Total k.w. hours generated at power-house.}}$$

and represents the operating expenses per k.w. hour at power-house switchboard.

Column M is:

$$\frac{\text{Column F (of table not published)}}{\text{Total k.w. hours delivered to contact shoe, annually,}}$$

and represents the operating expenses per k.w. hour at contact shoe.

Column N is:

$$\frac{\text{Column G (of table not published)}}{\text{Total k.w. hours delivered to motor terminals annually,}}$$

and represents the *total cost per k.w. hour delivered to motor terminals, exclusive of fixed and operating charges on electric locomotives.*

The cost per k.w. hour at motor terminal differs from the cost per k.w. hour at the contact shoe only when batteries are carried on the locomotives, in which event the cost per k.w. hour at the motor terminals is increased over the cost per k.w. hour at the contact shoe by the cost of energy lost in the batteries.

Column J is:

$$\frac{\text{Column B (of table not published)}}{\text{Column I}}$$

and represents the operating expenses per electric locomotive mile. The values in this column are directly comparable with values now obtained in the present steam locomotive service, except that the operating expenses for steam locomotives as shown by the performance sheets of the Motive Power Department do not include any charge for water. From the best information available, the cost for water for the present service on this division is about .987 cents per locomotive mile, which amount added to the present cost as shown on the locomotive performance sheets, gives an amount which should be compared with the values in Column J.

Column K is:

$$\frac{\text{Column C (of table not published)}}{\text{Column I}}$$

and represents the fixed charges per electric locomotive mile, and is here tabulated merely as a step in obtaining

TABLE IV.—Table of Estimates on Plans for Proposed Electrical Equipment of the N. Y. C. & H. R. R. R. Between Grand Central Station and Mott Haven Junction.

Plan.	CHARACTER OF STATIONS ETC.	Operating expenses per k.w. hour at Power-House Switchboard. $H = \frac{E}{\text{Total k.w. hours at power-house}}$	Operating expenses per k.w. hour at Contact Shoe. $M = \frac{F}{\text{Total k.w. hours at contact shoe}}$	Total cost per k.w. hour at Motor Terminals. $N = \frac{G}{\text{Total k.w. hrs. at motor terminals}}$	Operating Expenses per Locomotive Mile. $J = \frac{B}{I}$	Fixed Charges per Locomotive Mile. $K = \frac{J}{C}$	Total Charges per Locomotive Mile. $L = (J + K)$
1.	Direct current power station at center of line and contiguous to tracks. 600-volt working conductor, no batteries	.447c	.60c	1.06c	14.02c	6.58c	20.60c
2.	Same as No. 1, with batteries in power-house	.472	.66	1.137	14.65	6.71	21.36
3.	Same as No. 1, with battery sub-station near Grand Central Station and Mott Haven Junction	.475	.668	1.20	14.7	7.25	21.95
4.	Alternating current power-station on river front near center of line, with rotary converter sub-stations near each end of line. 11,000 volt A. C. and 600 volt D. C.	.572	.715	1.287	15.2	7.58	22.78
5.	Combined D. C. and A. C. Power station at Harlem River near one end of line and one rotary converter sub-station near the other end of line. 11,000 volt A. C., 600-volt D. C., no batteries	.570	.666	1.19	14.7	7.18	21.88
6.	Direct current feeders from Manhattan Railway sub-station located near center of line. Transmission from sub-station to working conductor, 600 volts D. C. energy to be purchased	2.5	2.650	2.748	34.64	2.89	37.53
7.	Rotary converter sub-station at center of line. A. C. energy to be purchased from Manhattan Sub-station and transmitted at 11,000 volts. Energy to cost ½ cent less per k.w. hour than D. C. energy delivered	2.5	2.336	2.508	31.50	4.23	35.73
8.	Two rotary converter sub-stations, one near each end of line. A. C. current to be purchased from Manhattan sub-station near center of line	2.1	2.336	2.504	31.50	3.93	35.43
9.	Combined A. C. and D. C. power station near Harlem River at end of line. One sub-station near other end, and batteries carried on locomotives charged from working conductor	.519	.629	1.122	16.58	7.76	24.34
10.	One rotary converter sub-station near center of line, A. C. current purchased from Manhattan sub-station No. 7, batteries on locomotives charged from working conductor	2.12	2.4	2.502	34.40	4.08	38.48
11.	Direct current feeders from Manhattan sub-station No. 7 near center of line. Batteries on locomotives charged from working conductors	2.5	2.738	2.742	37.81	2.51	40.32
12.	Combined A. C. and D. C. power station at Harlem River near outer end of line. One sub-station near other end. Batteries in power station and sub-station. A. C. transmission 11,000 volts, D. C. conductors 600 volts	.55	.775	1.335	15.80	7.83	23.63

Column L (which is Column J plus Column K) and represents the *total cost per electric locomotive mile.*

While the results in Column L of Table 4 indicate that Plan No. 1 was the most advisable one to adopt, it was not seriously considered for the reason that it necessitated locating the power station in a part of the city where its erection would probably have been prohibited by the city authorities, but it was here introduced for comparison as indicative of the economy to be gained by placing the power station at the theoretical center of distribution. The same objections apply to Plans 2 and 3.

Plans 4 and 5 bring out quite clearly the difference in the cost of operation between two sub-stations and one, both plans permitting the location of the power station on the river front.

The difference in favor of Plan 5 is entirely due to the saving in labor of one sub-station.

Plans 6, 7 and 8 were studied with the object of ascertaining whether the purchase, instead of the generation of power, would offer a satisfactory solution of the problem.

The purchase of both D. C. and A. C. energy was considered on the lowest basis that it was thought possible for any existing company to furnish it, and it was found that the D. C. energy would cost the railroad company one-half cent more per k.w. hour than the A. C. energy, in consequence of the interest, depreciation, maintenance, etc., of the transmission lines, rotary converters and other sub-station apparatus which would have to be furnished by the energy producing company.

The prohibitive annual cost of these purchasing plans is at once observed by reference to Columns L and M, the plans only meriting consideration as representing a temporary arrangement that might be effected in order to allow rapid installation.

Owing to the more or less complex system of overhead or third rail yard construction made necessary by the nature of the case, and the advantages to be obtained by their elimination in the substitution of locomotives which could, for switching service, be self contained, though normally supplied with energy from the working conductors, a study was made of electric locomotives carrying batteries.

The results of these studies made under several different assumptions are shown under Plans 9, 10 and 11. From Columns L and N it is evident that whatever may be gained by the elimination of the overhead construction is largely offset by the additional cost of operation, although it will be observed that

the cost per locomotive mile of Plan 9 compares favorably with the cost in Plan 12.

Plan 12 differed only from Plan 5 in a slight reduction in the capacity of the converting apparatus in the power-house and sub-stations and the substitution therefor of two storage batteries (one located in or near the power-house and one in the sub-station) each of such capacity that it, together with only a portion of the main station and sub-station machinery, would be capable of taking over the entire load of the line for a short period of time in cases of emergency.

The additional first cost and the slight increase in annual expense (as compared with Plan 5) represented by a reserve station capacity of this nature, was thought to be of secondary importance only, in view of the increased reliability of operation thereby obtained. The increased cost of operation in this plan over that of Plan 5 is due to the fact that the battery maintenance was figured at 10% per annum, which is somewhat higher than is ordinarily assumed, and will probably be considered excessive by some.

A battery of this kind would not only serve as a reserve but would prove of considerable value as a regulator of potential along the line, and in addition it would, notwithstanding its inherent losses, tend to reduce the power-house operating costs by taking up the excessive load fluctuations of the system and permitting the load upon the engines to be maintained at or near their most efficient working capacity.

It was considered of the utmost importance in an installation of this magnitude that the number of interruptions of power supply be reduced to a minimum, that no device which could increase the safety and reliability of the plant should be omitted, and that the probability of future extensions of the electrical system should be considered. As best fulfilling the above conditions, therefore, Plan 12 was the one specifically recommended for adoption.

Operating Expenses.

A careful compilation of all the expenses entering into the operation of the present steam service was made, and the following comparative table (Table 5) of relative costs is believed to be correct, assuming that the present locomotives running between Mott Haven Junction and Grand Central Station should be abandoned and the service now performed by them dupli-

cated by electric locomotives operated in accordance with Plan 12. It is assumed that the electric locomotives will be operated by the same class of men as those who now operate the steam locomotives and that they would receive the same rate of pay that they now receive.

This condition is not favorable to electric traction, as it is not ordinarily necessary to have two men to operate an electric motor, but in the writer's judgment, it is not advisable to operate a service of this class under such exacting conditions without two men on each locomotive.

If the motor car system should be adopted, as it probably would be were the electrical equipment extended beyond Mott Haven Junction or if the forward guard or brakeman were allowed to take the place of the second man while passing through the tunnel and yards, a saving equivalent to his wages could thereby be effected.

With two men of the same skill as at present employed on the locomotives, the figures are as follows:

TABLE V.

	Steam	Electricity
Operating expenses per locomotive mile exclusive of fixed charges but including water, labor, cost of cleaning and repairing tunnel, and all other expenses of locomotive operation - - - - - - - -	23.05	15.80
Fixed charges per locomotive mile assuming that it now requires 40 locomotives to perform the present service and that 33 electric locomotives could perform the same service -	1.13	7.83
Total in cents - - -	24.18	23.63

From these figures it appears that while there would be a slight annual saving in operating expenses in favor of electricity, it is not sufficient to warrant its adoption on the grounds of economy in operation alone, although its adoption can be justified on other grounds.

These figures could be made more favorable to electricity were an optimistic view of many of its advantages taken, and the probability is that practical operation will show a somewhat greater gain than here indicated, but it has been deemed best by the writer to maintain a conservative view throughout the entire investigation.

It is, however, safe to conclude that the saving in operating

expenses by the electric system would be sufficient to offset the increased fixed charges due to the additional investment made necessary by its adoption.

The dynamometer car was operated by Edward C. Schmidt, Professor of Railway Mechanical Engineering of the University of Illinois. He was assisted by Messrs. J. J. Snodgrass and R. W. Lohmann.

Messrs. B. S. Harrison, Hugh Hazleton, R. W. Lohmann, J. J. Snodgrass, H. A. Strauss, and A. S. Courtright, assisted in the calculations and preparation of the report.

In connection with the investigation, a series of comparative acceleration tests of steam locomotives and electrical equipment were made at Schenectady, the results of which are set forth in another paper prepared by Mr. W. B. Potter and the writer, which is to be read at this convention.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 19th, 1902.

NEW ELECTRO-PNEUMATIC SYSTEM OF ELECTRIC RAILWAY CONSTRUCTION.

BY BION J. ARNOLD.

During the past three years, as many of the members of the INSTITUTE know, I have advocated the use of the alternating current motor for certain classes of railway work somewhat earnestly, and have often been asked by my friends why I believed so thoroughly in the alternating current motor, and have been questioned rather closely at times for particulars regarding a certain system which I have been working upon.

I wish to state that long before I had any fixed ideas as to a system of my own, a study of the railway question from an engineering standpoint partially convinced me of the necessity of the ultimate abandonment of the direct current motor for heavy and long-distance service, due to the low working voltage to which it was necessarily limited, the resulting heavy investment in transmission lines thereby required, and the many translations between the power station and the car when any great distance was taken into account.

An active connection with the development and construction of electric railways in this country impressed me with the correctness of my preconceived ideas to such an extent that they finally crystallized into a system of electric railway construction upon which I have been working for several years, and to which I have alluded from time to time without giving, to those not interested with me, any definite information regarding it, for reasons well-known to those working upon new devices.

I have constructed twenty miles of road for this system, together with the necessary trucks and motor equipments, and as I am reasonably sure of the interest you will take in this system, I feel warranted in presenting it to this INSTITUTE.

As I have previously stated before the INSTITUTE, I am particularly anxious that American engineers shall keep abreast with European practice in the development of the alternating current electric railway, and while some of my brother engineers may not agree as to the practicability of my ideas, there are others in the INSTITUTE who, I think, believe as thoroughly as I do in the alternating current motor for railway work, and whether my system proves the correct solution of the question or not, I firmly believe that the alternating current motor will finally prevail for heavy railway work.

The recent discussions of this question that have been going on between engineers in Europe and the United States have made the subject a live one at present, and this is my reason for presenting a brief description of one embodiment of my system at this meeting.

The principles underlying the system which I advocate and which I call an Electro Pneumatic System, are as follows:

1st.—A single-phase or multiphase motor, mounted directly upon the car, designed for the average power required by the car, and running continuously at a constant speed and a constant load, and, therefore, at maximum efficiency.

2d.—Instead of stopping and starting this motor and dissipating the energy through resistances, as is customary with all other systems known to me, I control the speed of the car by retarding or accelerating the parts usually known as the rotor and stator of the motor, by means of compressed air, in such a manner that I save a portion of the energy which is ordinarily dissipated through resistances, and store it to assist in starting the car, helping over grades, for use in switching purposes, and for the operation of the brakes.

3d.—By this method of control I secure an infinite number of speeds from zero to the maximum speed of the car, which may or may not be at the synchronous speed of the motor, for with the air controlling mechanism working compressing, the speeds below synchronism are maintained, and by reversing the direction of the air through the controller speeds above, synchronism may be attained for reasonable distances. This feature gives to the alternating current motor the element absolutely essential for practical railway work, for it permits a car or train to ascend a grade at any speed with the motor working at its maximum efficiency, and imparting its full power to the car. When decending the grade the motor may utilize its full power drawn from

the line in compressing air, or it may be used to compress air with the stored energy of the train, thereby acting as a brake.

4th.—By virtue of the air storage feature, each car becomes an independent unit and is capable, in case of loss of current from the line, of running a reasonable distance without contact with the working conductor, and this without the aid of storage batteries. This feature will enable a car to work on a high tension trolley wire or active conductor over private right of way, and allow the active conductor to be stopped where the private right of way ceases, and the car to proceed through a city or town on any tracks, whether electrically equipped or not, until it reaches the outskirts of the city or town where it can take up the working conductor again on private right of way. This feature is also valuable in switching work, for each car being independent it may leave the main line track and operate over switches or sidings without complicating the yards with additional overhead or third rail conductors, thus necessitating through line conductors over main line track or tracks only.

5th.—Since a single phase motor can be used the motors can be supplied with current from a single overhead wire or third rail, and with a single rail return circuit, thus permitting the overhead construction, or third rail construction, to conform to the standard of to-day, except that a much higher working voltage can be used, provided the insulation is taken care of. Furthermore, in steam railway work this system, by virtue of its single phase feature, will require the use of only one of the track rails for the return circuit, thus leaving the other rail for the use of the signal system, which, up to the present time, does not seem to have been satisfactorily solved without the use of one of the track rails.

6th.—The current will be taken from the working conductor at any voltage up to the limit of the insulation, and in case this voltage is high (I am building my line for 15,000 volts), a static transformer will be carried upon each car and the pressure reduced from the line voltage to the voltage of the motor, which in the case under construction is designed to be 200 volts. Where it is unnecessary to utilize so high a line pressure the motor may be designed for the working voltage, and the current fed directly from the working conductor into the motor, thus eliminating the static transformer. When a high voltage working conductor and static transformer is used, and it is thought advisable to use a working conductor through cities or towns, this working con-

ductor will be supplied with energy through a stationary transformer at each city limit, thus making the working conductor through the cities or towns safe.

7th.—By virtue of the speed of the motor and its constant load, either when the car is in motion or when it is standing still and the motor is compressing air, the variable load now customary in electric railway power plants is eliminated, and the power station works at practically a constant load, thereby eliminating a large part of the investment at present requisite in power station and line construction. Furthermore, by virtue of the air storage feature, each car, in the particular apparatus I have designed, is capable at any time when current is on the working conductor, of delivering to the car wheels a much greater torque in proportion to the capacity of the motor than is possible with any electrical system known to-day.

I believe that by the adoption of this system the following results will be accomplished:

1st.—The entire elimination of the present standard system of rotary converter substation plant, together with the maintenance thereof, and the cost of the necessary attendants.

2d.—The absorbing and rendering available for useful work in starting, or otherwise, of a large percentage of the energy stored in the moving mass which under the present methods of operation is dissipated at the brake shoes.

3d.—A large reduction in the first cost of electrically equipping long-distance railroads, thereby making it feasible, from an engineering and business standpoint, to equip many roads which cannot now be shown to be advisable, thus opening up the steam railway field to the industry in which we are now engaged.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 20th, 1902.

THE FUNCTION OF SHUNT AND SERIES RESISTANCE IN LIGHTNING ARRESTERS.

BY PERCY H. THOMAS.

INTRODUCTORY.

In a paper read before this INSTITUTE on February 14 of the present year, the writer treated the subject of static disturbances in high tension lines and discussed some types of protective apparatus—chiefly the choke coil, the static interrupter, and the multi-gap lightning arrester. The function of the choke coil or interrupter was described as the prevention of local concentration of potential in windings of transformers or generators, such as is caused by waves of static electricity; the function of the lightning arrester, to prevent an excessive rise of potential of the protected circuit above the earth. The lightning arrester has also a secondary function of great importance, namely, the suppression of the arc which tends to follow a simultaneous discharge to ground from two legs of a circuit. The object of the present paper is the description of a new method of enabling an arrester to suppress such an arc, which is, of course, backed by the power of the generating system. This principle not being directly involved in the question of the protection of apparatus from static strains, received but bare mention in the paper referred to above.

The type of arrester about to be described involves the use of series and shunt resistance in connection with a multi-gap arrester. This type is important, as it permits the use of a very low series resistance with the arrester, giving a comparatively

free discharge path to earth. That is, the chief advantage of the arrester using series and shunt resistance over that using only series, is the fact that the former may be made operative with a much smaller series resistance than the latter.

Some years ago, Mr. Henry Noël Potter discovered, in some investigations on lightning arresters for Mr. Wurts, that a voltmeter connected in multiple to some Wurts non-arcing metal A. C. arresters, prevented the formation of a permanent arc in the gaps. In this experiment a highly inductive circuit was being used, such as had been found very severe on the non-arcing power of these arresters. Investigation then developed the fact that the shunt path formed by the voltmeter was the cause of the suppression of the arc. Mr. Potter later made practical application of his discovery in the large generator switches at the power-house of the Niagara Falls Power Company. In these switches several breaks in series are introduced, some of which are shunted by resistance.

At a later date, Mr. Charles F. Scott proposed the use of this principle for the improvement of lightning arresters. Trial proved, however, that a great deal more was involved in the application of the principle of a shunt resistance to lightning arresters than to the large switches at Niagara, and it was found necessary to investigate the subject from the beginning. This work, which was carried out by the writer, developed some very interesting laws or principles, which will be fully discussed. The final result has been the design of a new type of commercial arrester, which includes not only a shunt resistance, but a series resistance as well. This arrester, which is adapted to A. C. circuits only, is called the low equivalent A. C. arrester, on account of its low spark gap equivalent.

Principle of Operation.

The complete lightning arrester embodying the shunting principles is shown in Fig. 1, and consists of a number of small air

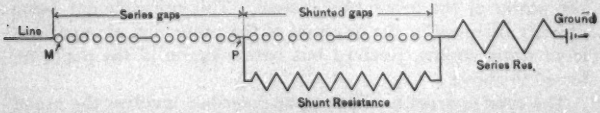

Fig. 1.—Low Equivalent A. C. Arrester, showing Series and Shunt Resistance.

gaps connected between line and ground, a portion of these gaps being shunted by resistance, marked " shunt resistance," and a

series resistance placed in the earth connection. The shunt resistance is usually placed as shown, next the series resistance, and preferably half of the total number of gaps are shunted.

It is evident that when the arrester is not in action, the point P at the junction of the shunted and series gaps is at ground potential, and consequently that the arrester will discharge whenever the voltage of the point M of the line reaches a potential above the ground sufficient to cause the series gaps to break down; that is, the voltage on the line necessary to cause the arrester to discharge, is that required to break down the series gaps alone, regardless of the presence of the shunted gaps. This has a very important bearing on the protective power of the arrester.

During actual discharge, the operation of the arrester is as follows:

When the series gaps break down, the resistance between the points M and P is momentarily reduced to practically zero, and the full amount of the potential of the line is then thrown on the shunt and series resistances. If this potential, which is thus abruptly applied to the resistances, is high, the shunted gaps will be broken down. This makes, for the instant, a direct path for the static discharge from line to series resistance. Theory and experiment both show that practically no greater voltage, provided it be suddenly applied, is required to break down both series and shunted gaps than the series gap alone. This result is due to the fact that the two sets of gaps are broken down separately, one after the other. If conditions are right, current from the generator will then follow the static discharge through the gaps, establishing an arc. The current will flow through the shunt and series resistances and usually through the shunted gaps, but if the various parts are properly proportioned, the shunt resistance will take enough current from the shunted gaps so that the arc cannot hold in the latter and will drop out. Once the arc drops out in the shunted gaps, it must pass through both resistances, which will reduce the current strength, and enable the series gaps to suppress it altogether.

The series resistance is found necessary for the successful operation of the arrester as outlined above, to prevent the enormous rush of current, which, on circuits of large generating capacity, would otherwise follow discharges and cause lights to dip and synchronous apparatus to fall out of step, as well as over-heating the arresters themselves. This series resistance

through which the discharge must pass is evidently in general an objectionable feature in the arrester, although it will be practically harmless if its amount is not too great. By the use of the shunt resistance, the value of the series resistance is kept comparatively small. This is the chief advantage of this type of arrester. A fuller description of the effect of the series resistance on the discharge of the line will be found in the paper to which reference has been made above.

Conditions Affecting Non-Arcing Power.

The capacity of an arrester to suppress or prevent the formation of an arc in its gaps after discharge, may be called its "non-arcing" power, and an arrester which is able to accomplish this result under all conditions for which it is designed, may be properly called "a non-arcing arrester." It is evident that an arrester will never be non-arcing when connected to a circuit whose normal electromotive force is high enough to cause the arrester to discharge. The non-arcing power of a combination of gaps and resistance under a given set of conditions will here be measured by stating the number of gaps required, under these conditions, to be just able to suppress the arc. The conditions determining the proper proportioning of parts in an arrester using shunt and series resistance may now be considered. Before taking up the subject of the shunting power of resistance, it will be necessary to outline the conditions covering the non-arcing power of a simple series of gaps with or without resistance in series, which is found actually to be the fundamental case.

Non-Arcing Power of an Unshunted Series of Air Gaps.

The use of a number of small air gaps in series in an arrester, rather than one large gap, is an essential feature in all arresters for high voltage circuits. The conditions affecting the non-arcing power of such a series of gaps are of two sorts. First, those involved in the physical and chemical construction of the gaps themselves, and second, those depending upon the constants of the circuit to which the gaps are connected. The conditions in the first class, being quite generally recognized, will be only briefly mentioned.

(1) *Non-Arcing Metal.*—There is a surprising difference in the non-arcing power of gaps of the same form but of different materials, even when tested under the same conditions. This very important fact was discovered by Mr. Wurts some years ago and has been fully described by him. Those metals which give

the greatest non-arcing power—commonly called non-arcing metals,—are zinc, bismuth, antimony, cadmium and mercury. The presence of zinc in an alloy will usually give this alloy a non-arcing quality. Copper, tin and iron are not suitable for lightning arrester work. The condition in which the terminal is left by a momentary arc, that is, whether it is pitted or whether it is beaded, so that the gap is partly bridged over by the melted material, varies markedly with different materials. This point is a very important consideration. Iron has a tendency to bridge the gap, while non-arcing alloy pits slightly, leaving the gap virtually in as good condition as before the occurrence of the arc. In choosing his non-arcing alloy, Mr. Wurts used such proportions of zinc and copper that the effect of the zinc, which pits, is just balanced by that of the copper, which beads.

(2) *Multi-Gap Principle.*—The fact that a series of gaps is a much more powerful non-arcing device than a single gap which requires the same voltage to start a discharge, is probably due partly to the chemical or electrolytic actions occurring at the surface of the terminals, and partly to the cooling effect of the metallic terminals, which, in the small gaps, are so close to the arc. When an arc is suppressed by the gaps of an arrester, the current drops out as it passes through its zero value, and the air rapidly regains its insulating quality, so that when the electromotive force is reversed and the current tends to build up in the opposite direction, the arc is suppressed since the gap has lost its conducting power. The remarkable speed with which incandescent air can become cool is shown by the fact that very rapidly moving objects viewed by the light of a static spark passing through air, appear stationary. This means that while the air has become incandescent and has cooled again, the moving body has not changed its position sensibly.

(3) *Length of Gap.*—With gaps between 1/64″ and 1/16″, the non-arcing power varies somewhat less than proportionally to the length of the individual gaps.

(4) *Minor Conditions.*—The temperature of the terminals of the gaps is quite an important condition, as a great increase of temperature reduces the non-arcing power of the gaps The non-arcing power of the so called "non-arcing" alloy falls off materially after very long continued hard service. This is probably because the zinc is gradually burned out.

Those conditions affecting the non-arcing power of a series of gaps which depend on the constants of the circuit to which the

gaps are connected, may be called the " circuit conditions." The "circuit" must include all apparatus actually connected to the system. Circuit conditions are, chiefly, the voltage of the generator, the capacity of the system to deliver current on short-circuit through the gaps, the equivalent inductance through which such current flows, the frequency of the system, and the phase of the generator e.m.f. at which the discharge starts.

The following laws have been experimentally determined with gaps of non-arcing alloy, each approximately 1/32″, and do not necessarily apply to other conditions without modification.

(1) *Generator Voltage.*—With the total power and the power

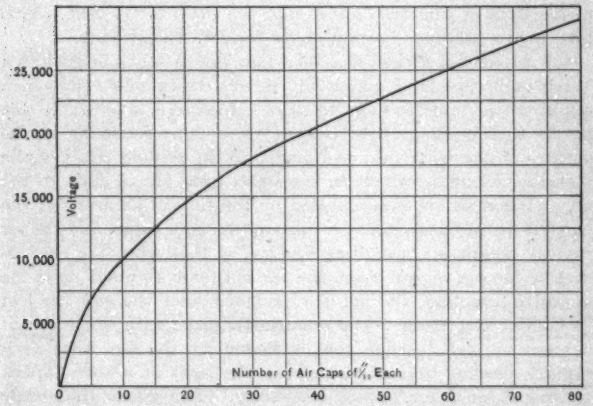

FIG. 2.—Number of Gaps necessary to withhold Normal Voltage with Sine E.M.F. Wave and no High Tension Lines Connected to Circuit.

factor of the circuit as a whole constant, the number of gaps necessary to suppress an arc is somewhere nearly proportional to the voltage of the generator. This number of gaps, however, does not increase quite as rapidly as the voltage. That is, if we place the gap across the terminals of a raising transformer supplied by a generator and then connect the secondary coils of the transformer in various symmetrical combinations, so as to give different voltages (in all cases using the whole of the transformer winding), under these conditions the number of gaps required is approximately proportional to these transformer voltages. If,

however, the strength of the current following a discharge, or the inductance of the circuit, is kept constant as the voltage varies, the number of gaps is by no means proportional to the voltage of the circuit.

It is interesting to note that the number of gaps required to withhold the generator voltage and prevent its breaking down the gaps without the aid of a static discharge, obeys an entirely different law from the number required to suppress the arc after a discharge. The number of gaps required to hold the given voltage under one particular set of conditions is shown in Fig. 2. This is to be compared with a straight line, which shows approximately for different voltages the gaps required to suppress an arc when once started.

(2) *Short-Circuit Current.*—The voltage, inductance, etc., remaining unchanged, the non-arcing power is proportional to a power of the short-circuit current between the first and the second, usually more nearly following the second. This law is not unexpected, assuming the cause of the holding of the arc in the gaps to be the heat generated, since the amount of this heat is proportional to the square of the current and to the resistance, the resistance, of course, decreasing with an increase of current. With large current and high power factor, the non-arcing power is more nearly proportional to the first power of the current, but with small current at low power factor, it follows the second power quite closely.

This law is a most important one as regards commercial lightning arresters, since the growth in the power of central stations means large currents flowing on short circuit, which in return requires many gaps, and since the minimum practical gap is soon reached, an excessive equivalent gap between line and ground will result. As long as plants were only very moderate in capacity, the multi-gap arrester without resistance was perfectly adequate for all cases, but with the very large installations of the present time, this is no longer true, and with such systems some resistance should be used to increase the non-arcing power.

In determining the short-circuit current that will flow through the arrester after a static discharge, not only the capacity of the generator itself to deliver current on short-circuit must be considered, but also that of all synchronous apparatus, storage batteries and even induction motors, under some circumstances. With two generators in parallel, more gaps are required than with

a single generator. If a resistance be placed in series with the air gaps, the amount of current flowing after a discharge will be reduced and fewer gaps will be non-arcing. This resistance has much the same effect, so far as the gaps are concerned, as reducing the capacity of the generators.

(3) *Inductance.*—With a given current and a given voltage, non-arcing power varies inversely as the inductance in circuit. This law is only approximate. With large amounts of inductance, the non-arcing power does not fall as fast as the inductance increases.

This is a most important condition, for the inductance of a generating system varies inversely as its power, other things being kept in proportion, so that as far as this condition alone is concerned, the large generator produces an easier condition for the gaps than a small one, since the inductance is less. On the other hand, the large generator will give a larger short-circuit current, which affects non-arcing power more nearly as the square, consequently the total result of increasing the capacity on the system is to reduce the non-arcing power of a given series of gaps.

The effect of the inductance in the circuit may be considered as a function of the energy stored electro-magnetically. This energy is equal to $\frac{1}{2} I^2 L$. When this stored energy is large, the wave form of the e.m.f. in the gaps is flattened so as to give a very short period for the small values of the current near the zero point of the wave. This, of course, reduces the opportunity for the cooling of the hot gases of the arc. In some cases, there may even be an increased voltage above the normal, due to the stored energy, although this rise will never be of serious moment, as even a small increase of normal potential will merely cause the gaps to continue to discharge. Experiment shows the effect of a given quantity of stored energy to be less effective in reducing non-arcing power on low voltage and large currents than on high voltages and small currents. This difference is quite marked.

The effect of inductance in the circuit is very noticeable to the eye and ear. When the inductance is large, the arc in the gap is much quieter, but more persistent and may continue as long as one second and then drop out. This delay in the suppression of the arc probably represents the period necessary to consume the energy stored in the magnetic field by the initial rush of current following the static discharge. This original discharge, having a very high current density, reduces the resistance in the gaps to

practically zero, and for several alternations thereafter this resistance is probably increasing period by period.

It is very difficult to compare the non-arcing power of similar gaps on different voltages, for of two circuits having the same power factor, one running at double the voltage of the other, that having the higher voltage will have an inductance and resistance four times as great as the other. To have the same stored energy in both cases, the first circuit must have half the current of the second, but half the current means a different heating effect, so that the conditions of the two cases as regards current are not comparable. Of the two circuits of different voltages, that of the higher is more difficult to control, as far as its inductance is concerned, but on the other hand, if the total power of the generating apparatus be the same in the two cases, it will have a small current, which means less heat in the arc.

For a circuit of given voltage, it is readily seen that the addition of inductance to a non-inductive circuit containing a series of air gaps, such as is under discussion, has the effect, if the inductance be comparatively small, of increasing the severity of the conditions on the gaps, for although the current is slightly reduced, yet the stored energy as a whole is increased considerably on account of the great percentage of increase of the inductance, but as more inductance is added, the current is more and more rapidly decreased, so that, although the inductance still increases, a point is finally reached at which the stored energy, which depends on the square of the current, will be as a whole decreased by the addition of further inductance. When this point is reached, further increase of inductance renders the conditions on the gaps easier.

(4) *Frequency.*—The frequency, at least between 25 and 60 cycles, is not very important in its effect on non-arcing power. The length of a single alternation is, of course, longer with the lower frequency, so that more heat units are produced by a given current before the zero point of the current arrives, but the time of duration of the period of small current, also lasts longer with the lower alternations, giving a compensating effect. The stored energy, of course, does not depend on the frequency. Experiment shows that if anything the lower alternations are the more severe on the lightning arrester.

(5) *Phase of e.m.f. at time of Discharge.*—The phase of the electromotive force wave of the generator at the instant of static discharge is an extremely important condition, for when the dis-

charge occurs with the generator e.m.f. nearly zero, no arc will be formed in the gaps with any condition of inductance or capacity of generator. There is, therefore, a certain portion of each alternation in which a discharge will be unable to start an arc; just how large a proportion of the alternation this will be, depends upon the non-arcing power of the gaps. In a successful arrester this period must include the whole alternation. If discharges are passed at random without relation to the phase of the generator e.m.f. in making tests of non-arcing power, it will be found that 25 to 50 or even 100 trials must be made to be certain of producing the severest condition. For this reason, there will be a great variation in the apparent severity of the discharges of arresters of this type on actual lines, for lightning occurs at random, at different phases of the generator e.m.f., causing a greater or less tendency of the arc to follow; this will naturally cause a larger or smaller flash in the gaps.

The chief conditions upon which the non-arcing power of a given series of air gaps depends have been considered, and the powers and limitations of the arrangement pretty well outlined. It is evident that for very large plants, the number of gaps necessary to secure satisfactory non-arcing power will render the protective power of the arrester inadequate. This difficulty may be overcome by the use of series and shunt resistance in the manner already described.

Shunt Resistance.

The effect of adding a resistance to shunt a portion of such a series of gaps as has just been discussed, will next be considered. If the addition of this shunt resistance is to better the conditions as regards suppressing the arc, then the proportion of parts must be such that without the shunt resistance the full number of gaps in the arrangement considered will fail to be non-arcing. In what follows, it will be assumed that the static discharge occurs at the phase most favorable for the continuance of the arc in the gaps. It will be readily seen that after the passage of the static spark, the current which will flow through the shunted gaps, will, on account of their resistance, produce a certain amount of voltage across the shunt resistance, which must, therefore, take a certain amount of current. This current will evidently be subtracted from the current in the shunt gaps. The decrease in the latter current increases the resistance in the shunted gaps, which throws more current into the shunt

resistance, and so on. If, now, the current in the shunted gaps is only just sufficient to maintain an arc when no shunt resistance is present, then the subtraction of a portion of this current will cause the arc to drop out in the shunted gaps. This forces all the generator current to flow through the shunt resistance. All current, of course, flows through the series gaps, and the series resistance. With the arc suppressed in the shunted gaps, the shunt resistance will then reduce the strength of the current in the series gaps, and, if it be great enough, will render them non-arcing. The laws determining when the shunt resistance will be able to withdraw sufficient current to cause the arc to drop out in the shunted gaps, have been determined as follows, the shunting power being measured by the greatest number of ohms per shunted gap allowable in the shunt resistance.

(1) *Number of Shunted Gaps.*—The amount of resistance which will allow the shunted gaps to be non-arcing is proportional to the number of these gaps.

(2) *Short-Circuit Current.*—The number of ohms allowable per shunted gap is proportional approximately to the square of the current which flows through the shunted gaps immediately following the static discharge. The "ohms per gap admissible" do not fall, however, quite as fast as the square of the current increases, so that doubling the current does not reduce the ohms per gap to quite one-quarter of its previous value.

(3) *Power Factor.*—The ohms per gap depend to a slight extent upon the power factor of the current following the discharge through the shunted gaps, being greater with low power factors. This is a fortunate circumstance, as circuits with low power factors are the most severe on arresters, and the ability to use a large shunt resistance allows the current and stored energy to be very materially cut down as soon as the arc drops out in the shunted gaps, which renders the series gaps more easily non-arcing.

(4) *Ratio of Series to Shunted Gaps.*—One very unexpected result is discovered, viz.: that the ohms per shunted gap depend largely on the ratio between the number of the series and shunted gaps. If the series gaps greatly exceed the shunted in number, the shunting power of the shunt resistance is much reduced, and vice versa, if the shunted gaps exceed the series gaps, the shunting power is increased. The objection to using more shunted gaps than series gaps is that a reduction in the protective power in the arrester will result, since more voltage will be required to

break down the shunted gaps and discharge the line, than is required to break down the series gaps.

(5) *Frequency.*—The frequency has little effect in the shunting power between 25 and 60 cycles; if anything the lower alternations are the more severe. It is fortunate that non-arcing power is nearly independent of frequency, as standard arresters may be designed for use upon circuits independent of frequency.

Method of Design of Arrester.

With the above outline of the laws governing the shunting power of resistance, it is now possible to outline a method of designing an arrester which will be perfectly non-arcing under any conditions assumed. First, determine the current given on short-circuit by the system. In doing this, the following factors must be considered.

(*a*) *Generator Field Reaction.*—As this is roughly proportional to the current, its effect will be the same as a resistance in series with the circuit and its equivalent ohms may be determined from the characteristics of the generator.

(*b*) *Inductance and Resistance.*—The true inductance of the armature which must be separated from the field reaction, the effect of all synchronous apparatus, which for the moment will act as a generator, the resistance and inductance of the line, transformers and auxiliary apparatus must be determined. When all these characteristics are together considered, the approximate short-circuit current and the stored energy may be approximated.

A number of gaps which is able to withhold the maximum normal line voltage with a suitable margin, must then be chosen. If this number of gaps, unaided by resistance, is able to suppress the short circuit current with the given amount of stored energy, the arrester may be considered complete. If such a series of gaps is not non-arching with the given conditions, the number of gaps should be doubled and one-half of them shunted by resistance and a series resistance added. The total amount of resistance must be such as so to cut down the short circuit current, that the series gaps will be non-arcing with the actual stored energy of the system. The largest possible portion of this resistance should be shunted, consistent with the ohms per shunted gap being sufficiently low to have the shunt effective. The remaining part of the resistance will constitute the series resistance. It may thus be seen that the use of series and shunt resistance may be made

to give the freest practicable discharge path for a given set of conditions, with the multi-gap type of arrester, and at the same time be non-arcing under all the given conditions.

Method of Investigation.

A brief description will be given of the method of making the experiments from which the laws stated in this paper were determined. Tests have been made on a number of different generators, and at a number of different voltages. In each case, the diagram of circuits was in effect like Fig. 3, except that in some cases raising transformers were omitted.

A is the generator supplying current to the gaps; R the raising transformer sometimes used to obtain the required voltage on the gaps. At D are the gaps to be tested; C and R are either

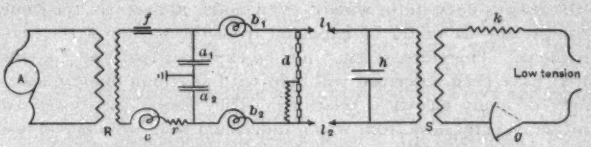

Fig. 3.—Diagram of Connections for Tests on Non-arcing Power.
a_1 b_1 a_2 b_2 = Static Interrupter.
A and R = Power Circuit.
r and c = Adjustable Resistance and Inductance.
d = Gaps being tested.
f = Fuse to Open Arcs.
l_1 l_2 h = Gaps and Condenser to Produce Static Sparks.
S = Raising Transformer for Static.
g = Swinging Switch.

inductance or resistance or both, placed in the main circuit to control the short-circuit current or the stored energy. B_1 B_2 are small choke coils in main circuit. A_1 and A_2 condensers to ground. A_1, B_1 and A_2, B_2, form two single-pole static interrupters to protect the raising transformer from the static strains produced in sending sparks over the gaps. F is a fuse used to open the main circuit when the gaps fail to interrupt the arc. This fuse, which usually consisted of one or more strands of No. 23 German silver wire, in a long tube, was found to open the circuit easily under the worst conditions tried.

To obtain the exciting static spark, a high tension transformer was used at S, with a ratio suitable for breaking down two gaps, L_1 and L_2, which were so adjusted that the discharge of the condenser H, resulting from their breakdown, was sufficient to force a discharge across the gaps at D. A resistance was used in series

with the low tension winding of this transformer to prevent any current from flowing from s through the gaps, etc., other than the charge of the condenser. The circuit of this transformer is closed on the low tension side, whenever a spark is desired, by a swing switch with a long arm making momentary contact at G. The apparatus was so adjusted that for each swing of the switch a clear, single, purely static spark crossed the gaps at D.

In making the tests, a great many combinations of inductance and resistance were used, and in each combination several numbers of gaps, and with each number of gaps from twenty-five to fifty sparks were passed, so that the phase of the wave most favorable for the arc's holding was practically certain to be tried.

This sort of testing is very laborious, very slow and involves considerable risk to apparatus, and the results when obtained will always vary quite widely, even under apparently the same conditions—as would be expected from the nature of the phenomena. Therefore, it must not be expected that the relations that have been described will hold with anything like the accuracy of many electrical relations. They should be considered rather, general laws from which individual tests will vary in one direction or the other, more or less, on account of ever changing secondary conditions.

In the use of series resistance in lightning arresters, there is a great temptation to limit the short-circuit current to an unsafe degree, as this reduces very much the difficulty of constructing a non-arcing arrester. Prevention of an arc is in itself a comparatively easy matter, but to secure good protection at the same time, the short circuit and the arc through the gaps cannot be strictly prevented but must be allowed to occur and then be suppressed. This is the difficult problem. The use of shunt and series resistance furnishes a means of reducing very materially the obstacle offered by series resistance to perfectly free discharge. Any further steps in the same direction should be welcomed.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 20th, 1902.

THE ELECTROSTATIC WATTMETER IN COMMERCIAL MEASUREMENTS.

BY MILES WALKER.

That a quadrant electrometer may be used as a wattmeter for measuring power has been known for many years. In the *Transactions of the Royal Society* (1891), Vol. 182, p. 519, will be found a discussion upon the subject by Ayrton, Perry and Sumpner, in which the precautions to be adopted in order to make a successful instrument are considered.[1] In 1898 Prof. Ernest Wilson[2] published the results of some experiments which showed the accuracy of the instrument at all power factors. Mr. Addenbroke in a paper before the International Electrical Congress at Paris in 1900[3] showed how the instrument could be arranged for universal electrical measurements. Nevertheless, the electrostatic wattmeter is almost unknown to electrical engineers, and certainly its advantages over other types of wattmeter are not fully appreciated. These advantages may be enumerated as follows:

(1) It can be made to give very accurate readings at low power factors.

(2) It is particularly well adapted for high voltage work, because it does not require a high non-inductive resistance.

(3) It is cheap and simple in construction.

(4) When constructed for low voltage work it will not be so likely to be burned out by accident as an ordinary wattmeter.

1. See also Prof. J. A. Fleming's Alternate Current Transformer, Vol. II, p. 551.
2. *Proc. Roy. Soc.* (1898,) Vol. 62, p. 356; also *Elec. Review*, London, March 4, 1898.
3. *Electrician* (London,) Oct. 5, 1900; also *Elec. Eng.* (London,) Feb. 2, 1900.

(5) By the use of suitable adjuncts the same instrument may be used to measure any power from 1 watt to 5,000 kilowatts.

(6) Its operation is based upon simple laws, so that when its needle is controlled by gravity, it can be relied upon as a standard instrument.

The disadvantages connected with its use are:

(1) It is not portable.

(2) The controlling forces are in general small, so that the instrument though dead-beat, is slow in reading.

(3) Its general behavior must be understood by the operator.

I propose in the present paper to discuss the principles that underlie the design of the electrostatic wattmeter for commercial work, and some of the uses to which the instrument may with advantage be applied. I am indebted to the Westinghouse Electric & Manufacturing Company for having had the opportunity of experimenting on this instrument, and to Mr. Percy H. Thomas, whose ideas and suggestions have been invaluable. It is one of the characteristics of American firms which have helped them to attain their present high position in the manufacturing world, that they are not afraid to spend a little money on theoretical investigation wherever there is a fair chance of some point being gained.

In designing an instrument for any class of work, it is desirable to know approximately the forces upon the moving part. The method of calculating the forces on the needle of a quadrant electrometer, as given in the standard text-books, does not appeal to the ordinary engineer, because the result is not expressed in the units with which he customarily deals. The following simple method is perhaps more acceptable:

Consider a U-shaped piece of metal C, Fig. 1, embracing a sheet of metal B. Let the size of the plates be great compared with the distance s between them. Let B be constrained so that it can only move in its own plane along the line O X. Let the length B in the direction at right angles to O X be l. Let v = number of volts of potential difference between B and C. Then $v/300$ is the number of electrostatic units of potential difference.

If A is the effective area on the upper side of B, $2A$ is the total effective area.

The total charge Q on the plate B will be

$Q = (2A/4\pi s) \times (V/300)$ electrostatic units of quantity.

The total store of energy in the electrostatic field will be

$$W = \tfrac{1}{2} \frac{V}{300} Q = \frac{A}{4\pi s} \times \frac{V^2}{90{,}000} \text{ ergs.}$$

Suppose, now, that the plates are connected to a generator so that the voltage between them remains constant no matter how they are moved, and the plate B is moved through a short distance dx so as to alter A by a little bit d A. The little change in the store of energy will be

$$d\,W = (d\,A/4\,\pi\,s) \times (V^2/90{,}000)$$

From Fig. 1, $d\,A = l\,d\,x$, and since the mechanical work done in moving the plate must equal the electrical work dW, we must have $d\,W = F\,d\,x$, where F is the force upon the plate. Therefore

$$F = (1/4\,\pi\,s) \times (V^2/90{,}000) \text{ dynes.}$$

If the plate B instead of moving parallel to itself moves about a center as at Fig. 2, we have $d\,A = r^2\,d\,\theta$, and $d\,W = T\,d\,\theta$, so that the torque

$$T = (r^2/4\,\pi\,s) \times (V^2/90{,}000)$$

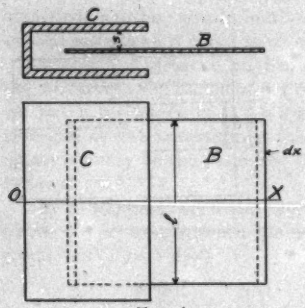

FIG. 1

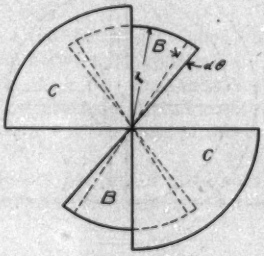

FIG. 2

where T is in dynes at a centimetre, r and s are in centimetres and V in volts.

$$\text{Let } (r^2/4\,\pi\,s \times 90{,}000) = k.$$

Take now the quadrant electrometer Fig. 3 and let the pressure between the needle and one set of quadrants be V volts and the pressure between the needle and the other set be $V + a$. Then, as one set is pulling one way and the other set the other, the torque is proportional to the difference between the squares of the voltages, or

$$T = k\,[(V + a)^2 - V^2] = k\,(2\,a\,V + a^2).$$

If we connect a quadrant electrometer to an electric circuit in the manner shown in Fig. 4, in which the current to the motor is

passed through a non-inductive resistance of R ohms, causing a drop of a volts, the torque on the needle at any instant will be

$$T = k\,(2a\,V + a^2) \qquad (1)$$

If, now, V is large compared with a, we have approximately

$$T = 2k\,a\,V = 2\,R\,k \times V\,c$$

The power supplied to the motor is $V\,c$ and if the needle is suspended so that its deflection is proportional to the torque, the deflection will be approximately proportional to the power supplied to the motor.

In the case of the alternating current we must take for V and a the expressions $\sqrt{2}V \sin 2\pi n t$ and $\sqrt{2}\,a \sin (2\pi n t + e)$, respectively, where e is the angle of lag. Substituting these values in equation (1), integrating throughout one complete

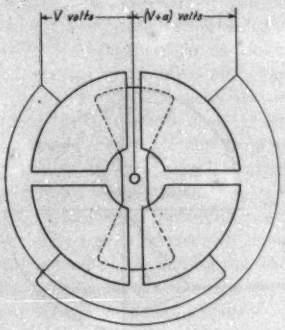

FIG. 3

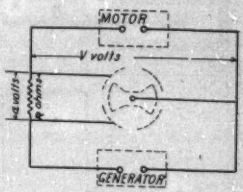

FIG. 4

cycle and dividing by 2π, we get the mean value of the torque throughout the cycle.

$$T = 2\,V\,a \cos e + a^2 = 2\,R\,k\,\left(V\,c \cos e + \frac{c^2 R}{2}\right)$$

The electrostatic wattmeter reads the power correctly whatever be the shape of the wave form, for at any instant the turning moment is proportional to the instantaneous value of the power and the needle takes up a position that corresponds with the average of the instantaneous turning moments.

It will be seen that the term a^2 is independent of the power factor $\cos e$, so that, when e is great, a considerable error may be produced in the measurement of the power, unless we take some precautions either to correct for this term or eliminate it

altogether. Several methods are employed by the Westinghouse Electric and Manufacturing Company for eliminating the term a^2 when working with low power factors. The best method to adopt in any particular case depends upon the kind of measurement that is being made. When working with high voltages, in measurements upon insulation losses, it is convenient to use only a fraction of the total voltage for the term V. The reason for this is that if we put 30,000 or 40,000 volts between the needle and quadrants we would be troubled with brush discharges, unless a very large instrument with large rounded conductors were employed. It is more convenient to take a tap off the transformer supplying the power and make the connections as in Fig. 5. If the ratio between the total voltage of the transformer and the voltage upon the needle be n, we may eliminate the a^2 term by putting in series with the transformer, at the terminal opposite the one to which the quadrants are attached, another non-inductive resistance, such that the drop in that resistance is equal to $a\,(n/2-1)$.

Suppose, for instance, that $n = 4$ and that to get a good reading we have a resistance of 0.1 ohm between the quadrants. If we put a resistance of $0.1 \times (4/2-1) = 0.1$ at the opposite terminal of the transformer the instrument will read correctly whatever may be the values of V, a or e. The proof of this is as follows:

The voltage between the needle and one set of quadrants is $(V/n + a/2)$ and between the needle and the other set of quadrants it is $(V/n - a/2)$

$$T = k\left[\left(\frac{V}{n}+\frac{a}{2}\right)^2-\left(\frac{V}{n}-\frac{a}{2}\right)^2\right]=\frac{2\,k\,V\,a}{n}$$

The simple application of this rule occurs when $n = 2$. In this case $(n/2-1) = O$, so that no additional resistance is required. In making measurements at pressures of 10,000 volts, it is convenient to connect the needle to the middle point of the transformer supplying power, and then the a^2 term is eliminated.

In other cases where it may be inconvenient to insert the additional resistance, an ampere-meter may be inserted, from the reading of which a may be calculated and the readings corrected. The term a is equal to $c\,R$. The calibration of the instrument and correction of the readings may be carried out very simply in the following manner: One pair of quadrants is connected to the needle and a continuous voltage V_1 (say 100 volts) is ap-

plied between the needle and the other set of quadrants. From the deflection D_1 produced we get the constant of the instrument from the formula

$$K D_1 = V^2_1$$

In any measurement of power if our arrangements are such that the a^2 term does not appear, then for any deflection D we calculate the power from the equation

$$\text{Watts} = (n K D/2 R)$$

But, if we cannot neglect the a^2 term we use the formula

$$\text{Watts} = \frac{n K D}{2 R} + \left(\frac{n}{2} - 1\right) C^2 R$$

The instrument connected up as in Fig. 5 (preferably with $n = 2$) is suitable for making measurements on dielectric losses in insulating material. In these tests there is no objection to

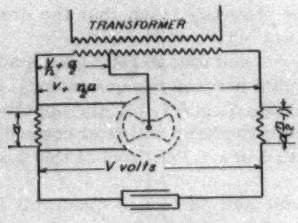

FIG. 5

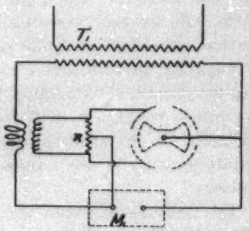

FIG. 6

making R very large so that good deflections may be obtained even when the current is exceedingly small. For instance, the power supplied to a few square inches of paper subjected to a pressure of 20,000 volts between metal plates may be measured with considerable accuracy.

The accuracy of this instrument with low power factors, its wide range and freedom from burning out, make it suitable for general testing purposes, whenever low power factors are likely to be met with. It is well-known that when the power of a 3-phase motor is measured in the ordinary way, with two successive readings on a wattmeter, one of these readings will be negative, or of very low power factor, when the motor is lightly loaded. We may have to take the difference between two readings, both of which are inaccurate on account of the effect of the low power factor upon an ordinary wattmeter, and the final

results will be very far indeed from accurate. An electrostatic wattmeter may be made to read power supplied at pressures as low as 100 volts, but in order to get good forces upon the needle it is desirable to increase the voltage a between quadrants. This necessitates the elimination of the a^2 term in equation (1). The best method of doing this for low voltage commercial work is that shown in Fig. 6.

T_1 is the transformer supplying the power to be measured.

M_1 is the apparatus absorbing power.

T_2 is a series transformer of suitable ratio, whose secondary is connected in series with a non-inductive resistance R. One pair of quadrants is attached to one end of this resistance and the other pair to the other end, the needle being connected to the opposite side of the system. The middle point of the resistance R (or if preferred, the middle point of the secondary of the transformer) is connected to the same terminal of the apparatus absorbing power as the primary of the series transformer. If a is the voltage across the resistance R, it is easy to see that the torque

$$T = k\left[\left(V + \frac{a}{2}\right)^2 - \left(V - \frac{a}{2}\right)^2\right] = 2\,k\,V\,a$$

The series transformer may be made so that the error due to its use is not more than one part of one thousand on high power factors, and one part in one hundred on low power factors.

A simpler method, though not quite so satisfactory, is that shown in Fig. 7. Here an auto-transformer T_3 has its middle point and one terminal connected to the resistance R, and the two outer terminals are connected to the quadrants. The middle point of the transformer being connected directly to the apparatus M in which the power is absorbed, the a^2 term is completely eliminated.

For polyphase work, it is convenient to use an instrument with two needles on the same shaft, just as in an ordinary polyphase wattmeter. The connections for a 3-phase instrument are shown in Fig. 8.

For a standard instrument, in which the deflecting forces are not too small, a bifilar suspension is the most satisfactory means of controlling the needle. Several precautions, however, must be taken to make a bifilar suspension satisfactory. The well-known formula for this suspension tells us that for small deflections the turning moment in grams at a centimetric =

$$\tfrac{1}{4}(1-m^2)(P\,y\,z/L)\sin\theta$$

where m is the ratio between the difference and the sum of the tensions in the fibres. P is the total weight of the needle in grams, y the distance between the fibres at the top, z the distance between the fibres at the bottom, L the length of the fibres and θ the angle turned through. All the distances are in centimetres. From this it is seen that it is very necessary to keep the tensions in the two fibres constant. A very good method of doing this is to hang the block to which the fibres are attached to short strips of phosphor-bronze at a considerable distance apart in the manner shown in Fig. 9. A line joining the strips

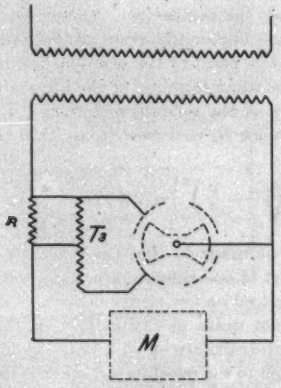

FIG. 7

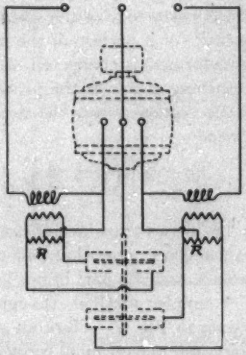

FIG. 8

is at right angles to the line joining the fibres, so that the block is free to tilt and equalize the tension in the fibres. By the addition of small weights screwed into two projecting arms, the ratio between the tensions may be adjusted to any degree of precision, and when once adjusted is independent of changes in the leveling of the instrument.

It is desirable to have the distance between the fibres as great as possible, so that microscopic changes in this distance from accidental causes will not change the constant of the instrument. From $\frac{1}{8}''$ to $\frac{1}{4}''$ makes a good working distance, if care is taken to make the point of suspension of each fibre perfectly definite.

Fine phosphor-bronze strips make strong and satisfactory sus-

pending fibres. The spindle of the needle should be fairly heavy so that the tension of the fibres is not altered perceptibly by small unbalanced electrostatic attractions. By putting weight in the spindle, the moment of inertia of the needle is very little increased. The needle should be made as rigid as possible and with a very small amount of inertia. For high voltage work, the forces upon the needle are so great that a single needle is sufficient. For low voltage work it is best to use a number of

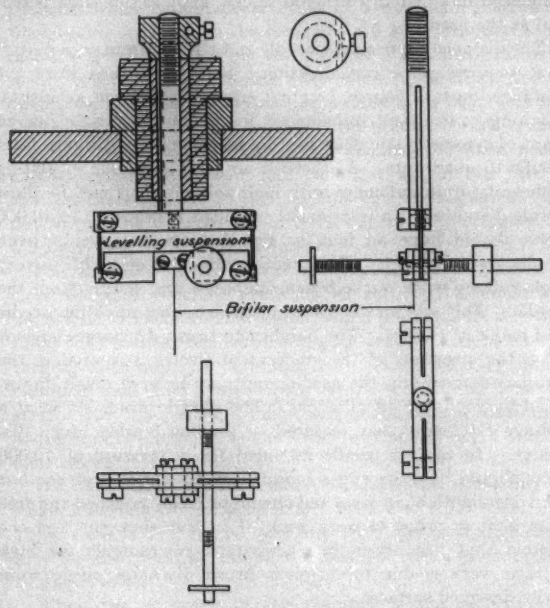

FIG. 9

small needles in a multicellular instrument. The moment of inertia of the needle, even if its thickness remains constant, goes up as the fourth power of its linear dimensions; whereas, the turning moment only goes up as the second power. A number of small needles may, therefore, be made more rigid and with smaller moment of inertia for the same turning moment than one big needle.

The needle and all attachments must be so shaped and guarded as to have no forces upon them except those due to the quadrants. For this reason it is well to avoid making projections on the frame or stationary parts of the instrument that can attract or repel any part of the needle. All visible parts of the needle and its spindle should as far as possible be figures of revolution, so that even if there is an unsymmetrical field outside the quadrants, it cannot produce a turning moment. The mirror should be placed in a cylindrical metal screen, kept at the same potential as the needle.

The distance between the needle and the quadrants is a matter that requires some consideration. In high voltage work the distance must, of course, be great enough to prevent accidental sparking over. Any unbalanced forces on the needle due to want of symmetry are decreased by increasing the distance from needle to quadrants. As there is no great difficulty in getting sufficient turning moment with high voltages, it is well to allow ample distance. An instrument intended to work up to 10,000 volts should have an inch as the shortest distance between needle and quadrants. The greatest difficulty met with in very high voltage work is the brush discharge that occurs from the needle. This sets up electric winds which react upon the needle and make it wander. The liability to brush discharge depends upon the steepness of the gradient of electric potential in the air space surrounding the needle, and may be very much diminished by rounding off all edges. The electric winds set in at a voltage far below that required to produce visible brush discharge. In fact, a needle intended for a pressure of 10,000 volts should have its edges rounded off to a radius of not less than one-eighth of an inch, and should be nicely polished and free from dust in order to work well. I believe that much of the trouble that has arisen in electrostatic instruments for high voltage work is due to incipient brush discharge rising from badly designed surfaces.

In a low voltage instrument the distance s between quadrants and needle is settled by very different considerations. Even when there is very little chance of sparking, this distance should not be reduced below a certain limit. If the constant of the instrument is to be very accurately maintained, about $\frac{1}{4}''$ should be the lowest limit. Any shifting of the needle up or down from its central position changes the constant. When the needle is exactly central, the rate of change of the constant is 0. For

small departures from the middle position, the rate of change of the constant is proportional to $4\,g/s^3$, where g is the little distance from the center. The smaller s is made, the more important become small movements of the needle in a vertical direction, due to expansion of the fibre or other accidental causes. However, if s be at least $\frac{1}{4}''$, a movement of the needle of 1/200 inch from the middle position causes an error of less than 0.05 per cent. A departure of 1/100 inch from the middle position, which should never occur in a well-made instrument, would cause a change in the constant of 0.2%. Another source of error arises from having the distance s too small in instruments controlled by a bifilar suspension. The attraction between the needle and the quadrants adds to or subtracts from the tension of the fibres, according as the needle is below or above the middle position. Where a fair distance between needles and quadrants is allowed, and sufficient weight put into the spindle, the error due to this cause is entirely negligible. The needle may be damped either by a copper cup swinging in a magnetic field or by a liquid damper.

The accuracy of an instrument depends greatly upon the closeness with which it preserves its zero. It is much more important to make an instrument which preserves its zero at all times than to make one which will give large deflections for small turning moments. A deflection may always be magnified or carefully read, but a wandering zero is a continual source of error. For this reason, a bifilar suspension with a considerable distance between fibres is the most satisfactory for a standard instrument.

We have used very successfully a suspension consisting of a single phosphor-bronze strip 0.001″ thick and 0.02″ wide. This shows very little "creep" and any error due to change of zero may be eliminated by taking the mean of readings on opposite sides of the zero.

When the accuracy of the readings is not so important, ordinary phosphor-bronze springs may be used to control the needle. For high voltage transmission lines, the electrostatic wattmeter has an advantage over other types for switchboard use, in not requiring a high voltage transformer. A good commercial instrument may be made for this purpose with a spring control.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 20th, 1902

ENERGY LOSS IN COMMERCIAL INSULATING MATERIALS WHEN SUBJECTED TO HIGH POTENTIAL STRESS.

BY CHARLES EDWARD SKINNER.

Those who have had occasion to test the dielectric strength of insulating materials by means of alternating e.m.f. are familiar with the fact that heat is always developed in these materials during such test. This is especially noticeable when the test is long continued at a point approximating the breaking down strength of the material. When the amount of material involved is large, ordinary indicating instruments will show at once that there is an actual loss of energy. The fact that energy loss exists under such conditions has been known for more than a decade, having been first shown by the experiments of Siemens, and later investigated by others. Published investigations on this subject relate almost entirely to the energy loss in the insulating material, or dielectric of condensers. The law of variation of loss, due to variation of voltage, was first announced by Mr. C. P. Steinmetz[1] early in 1892. At that time Mr. Steinmetz gave this loss the name of "dielectric hysteresis" because of its apparent similarity to the phenomenon known as hysteresis in iron and steel. Since that time other writers, notably Arno[2], Hess[3] and Borel[4], have made experiments from which they conclude that this energy loss is not in the nature of a dielectric hysteresis, and various theories have been advanced concerning its nature and cause.[5]

1. *Electrical Engineer*, March 16, 1892.
2. *Electrician* (London), March 3, 1893, and June 23, 1893.
3. *Journal de Physique*, April, 1893.
4. *Comptes Rendus*, May 23, 1893.
5. *The Electrician* (London), November 1, 1895.

It is not the object of this paper to discuss the theories of the origin or cause, but rather the effects of this loss, and in the absence of a name which can be accepted as descriptive and final, it will be spoken of as " energy loss " or " loss."

It is the intention to describe some of the methods employed and to give some of the characteristic results obtained from tests made on various materials used in commercial manufacture, and also on the insulation of finished apparatus. These tests have been made from time to time during the last five or six years, and have covered a great variety of materials. The major part of the tests, however, have been made on materials of a fibrous nature, such as paper and cloth, both in the treated and untreated state, and the discussion will be largely confined to this class. By treated material is meant a paper or cloth coated with some sort of insulating varnish. The samples used were taken from stock, and standard manufacturing methods were followed as far as possible in preparing them for the tests.

The action of ordinary commercial insulating material under high potential stress is usually so erratic, owing to surrounding influences, such as temperature, moisture, ventilation, etc., that a considerable number of observations are usually necessary in order to reach any satisfactory conclusions. For this reason the specific tests which are given in this paper are intended to show characteristic and not quantitative results, and are, therefore, not to be taken for other materials or even for other samples of the same material. Individual tests are of little value except as they fit in a series, or, unless the conditions surrounding them are known to the minutest detail.

For these tests alternating current at the standard frequencies of 25, 60 and 133 cycles was used, the e.m.f. varying from a few thousand volts to upward of 100,000 volts. The majority of the tests referred to were made on material subjected to a potential stress much in excess of that ordinarily used in actual practice, this being done both on account of the fact that the various phenomena are much more marked at the higher stresses, and also because a much smaller amount of material could be used for each individual test. The results, while being true for potential stresses, are of little commercial importance in ordinary low potential apparatus. They become, however, of the greatest importance in very high potential working, and especially so with condensers for use on high potential circuits. The results also have a direct bearing on the question of long-

continued tests of the dielectric strength of finished apparatus at very high voltages. The various phenomena noted are so inter-dependent that it is difficult to describe one without referring to others, and at times it will be necessary to anticipate results which are to be described later.

VARIATION OF TEMPERATURE DUE TO VARIATION OF STRESS.

When an alternating high potential stress is applied to insulating material, the temperature of the whole mass rises, but owing to the fact that all insulating materials are poor conductors of heat, the temperature of the inner portions rises above that of the outer portions, which have a better opportunity of dissipating their heat. A considerable number of tests have been made to determine the rise of temperature in the interior of a mass of insulating material under different conditions of stress. Usually these tests did not include the measurement of the amount of energy loss, as the results sought were the ventilation required under working conditions and the dielectric strength at various temperatures. The tests were usually made by placing the material between metal plates, which were connected to the terminals of a high potential transformer. The plates employed for this purpose should always have well-rounded edges to prevent the undue stress which occurs at sharp corners. The size of the plates varied in different tests, but the most satisfactory results were obtained with plates approximately 9″ in diameter, whose edges were rounded to a radius of about 1½″.

Various methods of measuring the temperature were tried, but only one gave entire satisfaction. A mercury thermometer inserted in the material gave trouble, especially at the higher potentials, as the mercury was vaporized by the static discharges in the thermometer tube. A small coil of very fine copper wire was placed in the material and the temperature determined by its increase of resistance. In long-continued tests this method was found unsatisfactory, on account of the rapid oxidation of the copper in the presence of the ozone always generated by such tests. The most satisfactory temperature readings were obtained by placing at the point where the temperature was to be measured, a copper-lead thermo-junction connected to a sensitive galvanometer. The outer ends of the couple were kept at 0° C. by being placed in ice water. By properly insulating the galvanometer, it was found entirely feasible to take readings with a potential stress of 30,000 volts or more across a ¼″ layer

of material, with this junction at the center. In some tests a number of junctions were placed at different points in the material, in order to map out the temperature of the various parts.

In a number of tests the material was arranged as above and then placed in a box in which was located an electric heater, a fan motor being used to circulate the air over the heater and through the box, so that any desired initial temperature could be secured and with care the surrounding temperature regulated throughout the test. In some instances insulation resistance was measured at intervals, the high potential wires being temporarily disconnected for this purpose. Usually the insulation resistance was so high as to be very difficult of exact measurement with the apparatus at hand.

The test samples used were built up to a thickness of $\frac{1}{8}''$ to $\frac{1}{4}''$ or more, and tests were made at different voltages up to the ultimate dielectric strength of the material. For most of the tests, current was obtained from a dynamo giving very approximately a sine wave of e.m.f. The results of this series of tests may be given as follows:

(1) With moderate stress the temperature of the material rises rapidly at first, then more slowly, then becomes constant. The actual rise in the temperature for a given voltage depends on the facility with which the material can dissipate its heat and on the temperature of the surrounding medium.

(2) As the stress is increased a point is finally reached where the heat is developed at a greater rate than it can be carried away, and temperature then rises until the material chars and break-down results.

(3) When material is not thoroughly dried, the temperature rises much more rapidly than in well-dried stock. The increased temperature cannot be accounted for by the increased $C^2 R$ loss due to lower insulation resistance. The heat generated tends to dry out the material and the temperature may fall as the drying proceeds.

(4) With a considerable area of material under test, the temperature of small portions frequently rises above that of the surrounding material to such an extent that on examination these portions are found much discolored, while the surrounding portions remain unchanged. This effect is especially noticeable with treated material not perfectly cured. The final break-down in such cases is invariably found in one of the heated areas.

(5) The final break-down in fibrous materials usually results from the burning of the material and not from mechanical rupture. When the e.m.f. applied is far above the dielectric strength of the material, the break-down may be due to a mechanical rupture. If, however, the e.m.f. is sufficiently low, so that an appreciable time elapses before break-down occurs, the break-down is probably due to burning caused by the heat generated in the material. There may be some attendant chemical action, but this is thought to be a result and not a cause of the excessive heat. The lower the e.m.f. applied, the longer the time required to produce break-down under a given set of conditions.

(6) It follows from (5) that if the temperature is kept low, either by providing good ventilation or by artificial cooling, the stress required to cause break-down in a time test will be much greater than if the material is not so cooled.

(7) The actual temperature measured in most fibrous materials before break-down occurred was usually 175° C. or more. In no case did a break-down occur directly at the point where temperature measurements were being made, and the temperature at the breaking down point was probably higher than measured, especially as the rise in temperature seemed to be very rapid at the point of break-down just before this occurred.

(8) With a given stress, the initial and surrounding temperature has much to do with the rise. This is due to the fact that the loss in the material increases rapidly with the temperature. For example, if the material and surrounding air are at 20° C. and the stress applied is 20,000 volts, the rise in temperature will not be nearly so great as if the initial and surrounding temperature is at 80° C. Tests have shown that break-down frequently results under the latter conditions from a stress that would not injure the material under the former conditions.

Fig. 1 gives some of the characteristic curves of rise in temperature in insulating material when subjected to high potential stress. Curves A, B and C were taken on a sample of untreated material which was quite porous and capable of absorbing moisture from the air. In this test the material was well-ventilated, so that any moisture could be quickly dissipated. The temperatures given are those actually measured, but probably do not represent the highest point reached in the material. Curve A shows the effect of moisture. The temperature rose very rapidly, reaching a maximum, then fell, and at last became

stationary. Curve B shows the effect on the same material after very thorough drying. Curve C shows the increased temperature due to a slight increase in the stress.

Curve D at the upper right hand corner of the figure, shows the

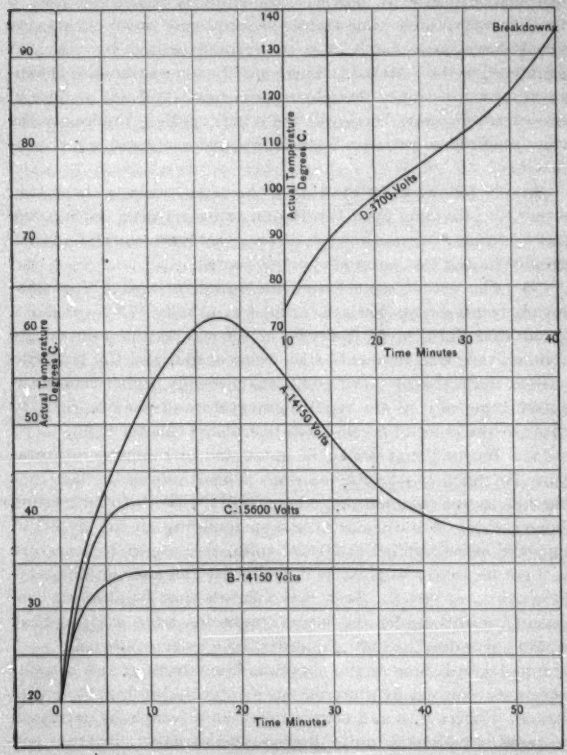

FIG. 1.—Showing Increase of Temperature in Insulating Material due to Stress.

rise in temperature in treated material when poorly ventilated, and the test continued until break-down resulted. Break-down in this particular test occurred at a point about 4″ from the thermo-junction when the measured temperature reached 135°

C. It is probable that the temperature measured was considerably lower than that reached at the point of break-down. The temperature of the surrounding air in this test was kept at 80°C. This curve shows the tendency of the temperature to become constant, but at a point slightly over 100° C. the loss becomes so great that the heat cannot be dissipated as fast as generated, hence the change in direction of the curve and final break-down. In numerous tests the material was found to be badly charred on the interior, without break-down having resulted. The curves shown are characteristic, and are of the same form as many others that have been taken.

Variation of Loss Due to Variation of Temperature.

The measurement of the energy loss due to high potential stress in a reasonably small sample of insulating material, presents a rather unusual problem. The voltage is high, the current small and the power factor very low. In many of the tests referred to in this paper, it was necessary to measure with some degree of accuracy losses of less than 100 watts at an e.m.f. of 20,000 to 40,000 volts, at various frequencies, with a power factor less than 0.1. The commercial instruments on the market are totally unsuited for this work.

Many of the measurements to determine the points under discussion were made by means of a calorimeter. This calorimeter consisted of a tank filled with mineral oil, in which the sample was placed. Calibration was effected by passing direct current through a resistance coil immersed in the oil and noting the rise in temperature of the oil, due to various amounts of energy absorbed. The rate of cooling from various temperatures was also carefully taken and was made use of in deducing many of the results. Great care was exercised to secure uniform temperature throughout the body of the oil by mechanical stirring, and the calorimeter was carefully shielded from drafts to prevent variation in the rate of cooling.

The material for these tests was usually built up in the form of a small condenser, with ventilating spaces between the plates, so that the temperature could be kept as nearly uniform as possible throughout the mass of the material. In the determinations of the variation of loss due to variation of temperature by the calorimeter method, the whole body of oil and insulation was brought up to some constant temperature, then the high potential stress applied. The rate of heating or cooling, as the

case might be, due to the loss in the insulation being greater or less than required to hold the calorimeter at this constant temperature, was then noted and the actual loss was derived by the use of the calibration curves of the calorimeter. These tests required great care, were very tedious and many corrections were required in deducing the results.

After a considerable amount of work had been done by the calorimeter method, a static wattmeter[6] was constructed and the work continued with this instrument. With this wattmeter, which was admirably suited to this work, a complete curve could be taken in the time required to determine a single point by the calorimeter method. It was a source of considerable satisfaction to find that the calorimeter and wattmeter methods checked each other with a very fair degree of accuracy, especially considering the nature of the materials on which the measurements were made.

In Fig. 2 are given curves which are characteristic in form for the increase in loss due to temperature. These particular curves were taken by the wattmeter method on a sample of material which had been used for some months for other tests and was known to be in the very best condition as regards moisture, etc. This general form of curve has been found to hold for all materials tested, although the rate of change of the loss and the amount of the loss per unit volume may be very different for different materials and even for the same sample of material under different conditions.

This series of tests has shown:

(9) The energy loss in fibrous material increases with temperature, the rate of increase in the loss being greater than the rate of increase in the temperature.

(10) The rate of increase depends upon the kind of material and on its condition with respect to dryness, etc.

(11) The local heating found in a mass of poorly ventilated material is due to a greater initial loss in one portion, causing increased heating, this in turn causing greater loss, etc., until the temperature finally reaches a point at which charring and breakdown result.

(12) These curves show that the rate of increase of loss is greater at high than at low temperatures, therefore giving the

6. For description of this instrument see paper entitled "The Static Wattmeter in Commercial Measurements," presented at this meeting by Mr. Miles Walker.

reason for the greater rise in temperature with a given stress when the initial temperature is high than when it is low.

Other tests have shown:

(13) That the loss increases very rapidly, indeed, when tem-

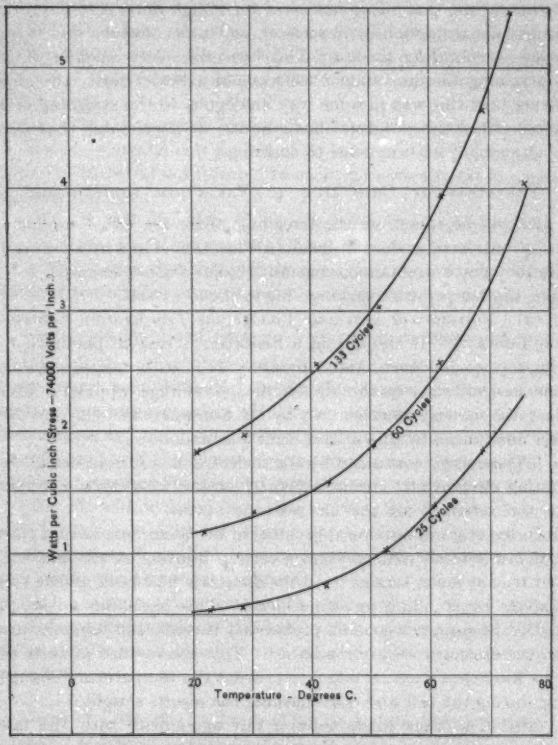

FIG. 2.—Showing Variation of Loss in Insulating Material due to Temperture and Frequency.

perature approaches the charring temperature of the material.

(14) Losses as great as 5 watts per cubic inch have been measured in material before serious injury resulted, due to

charring. A loss considerably less than this will, however, char the material in time unless special means are taken to dissipate the heat generated.

(15) It follows from considerations of rise of temperature due to increased stress, and increase in loss due to increase in temperature, that *a long continued test at high stress may seriously injure the insulation of a piece of apparatus without this being made apparent by the test.* This has often been spoken of as "straining the insulation" for want of a better term, the idea being that this was in some way analogous to the straining of a piece of metal beyond its elastic limit. It is probable that this "straining" is always due to charring.

Variation of Loss Due to Variation of Voltage.

As will be seen from the foregoing, there are two conditions, to be considered under this head: (a) Variation of loss with voltage, the temperature remaining constant; (b) Variation of loss with voltage, the temperature varying, due to the loss itself.

(*a*) *Variation of Loss with Voltage, the Temperature Remaining Constant.*—If the loss in a dielectric is due to partial conduction, as has been stated by Hess, it is to be expected that this loss will vary as the square of the voltage applied. This fact was shown experimentally by Mr. Steinmetz in 1892, and the law announced by him at that time was as follows:

"The energy consumed by the dielectric medium under alternating electrostatic strain is directly proportional to the square of the intensity of the electrostatic strain."

In his original note on this subject, Mr. Steinmetz stated that this law was not true beyond a certain limiting strain and was not true at lower strains until the dielectric had been allowed to recover by standing for some hours. This phenomenon noted by Mr. Steinmetz was in all probability the effect of temperature on the dielectric of his condenser. This shows that in tests of this kind care must be taken to prevent the temperature changing during the test and thus masking the results sought.

(16) The tests made show a fair agreement with the law above noted, the increase in loss usually being slightly greater than the square of the e.m.f.

A specific example illustrating this case is given later in some measurements made on the armature insulation of two of the 5,000 k.w. alternators built by the Westinghouse Electric & Manufacturing Company for the Manhattan Railway Company.

(*b*) *Variation of Loss with Voltage, the Temperature Varying, Due to the Loss Itself.*—It has already been shown that there is a rapid increase in the energy loss in a body of insulating material due to increase of temperature; also that the energy loss varies approximately as the square of the voltage when the temperature remains constant.

(17) It follows, therefore, that under the usual conditions of high potential stress the loss will increase more rapidly than the square of the voltage, because the temperature increases at the same time.

(18) The rate of this increase will depend on the facility with which the material can get rid of its heat, and on the length of time the material is subjected to each successive stress in carrying out the test.

(19) It will also depend on the initial temperature of the material and the temperature of the surrounding medium.

It will be seen that many of the conditions named under variations of temperature due to variation of stress apply to this case.

Variation of Loss Due to Variation of Frequency.

Like all the other phenomena described in this paper, it has been found very difficult to make check measurements on the losses of a large number of samples of materials at different frequencies and deduce a mathematical law from the results. In Fig. 2 are shown three curves giving results on a single sample of material tested at 25, 60 and 133 cycles.

(20) It will be noted from these curves that the rate of variation for this particular set of tests is approximately in proportion to the frequency at the lower temperatures, but follows a different law at the higher temperatures.

(21) In some other tests which were carefully made, the loss varied approximately as the square root of the frequency, but these results are not sufficiently well substantiated to announce as a law.

Energy Loss in the Insulation of Large Alternators.

Some measurements recently made of the energy loss in the armature insulation of the 5,000 k.w. alternators built by the Westinghouse Electric & Manufacturing Company for the Manhattan Railway Company, should prove interesting in this connection. These tests were made to check some of the results obtained on a smaller scale and to give some of the conditions

which exist when very high potential tests are made on large, high voltage apparatus.

These alternators are wound for a terminal e.m.f. of 11,000 volts, the winding being 3-phase star connected. In the design of the insulation, special attention was given to securing great dielectric strength, low dielectric loss and permanency under all conditions of operation. Preliminary tests in the factory had shown a dielectric strength of 80,000 to 90,000 volts for short applications of e.m.f. and a very small rise in temperature for a 30 minute test at 35,000 volts.

The tests to be described were made on two of these alternators after they had been installed ready for service. The accompanying diagram, Fig. 3, shows the connections of the various apparatus used. The primary current for the testing transformer was obtained from 350 volt (25 cycle) mains, and voltage regulation was by means of a large water rheostat in series with the primary of the testing transformer. The testing transformer had a capacity of 250 k.w. at 40,000 volts, loops being brought out to give steps of 5,000 volts on the high tension winding. Three instruments were used to measure the voltage: a direct reading voltmeter across the primary of the transformer, a voltmeter in series with a high resistance across a part or the whole of the high tension winding, and a static voltmeter across the high tension winding. Current was measured by means of a specially calibrated low-reading ammeter, with a series transformer arranged to multiply the current by 4. The small bank of lamps shown was used as a rough check on the ammeter readings.

The losses were measured by means of the static wattmeter referred to earlier in this paper. The quadrants were connected across a variable, previously calibrated resistance and the needle connected to the 10,000 volt loop on the high tension winding of the testing transformer. The deflection of the needle was read by a telescope and scale. The wattmeter was calibrated by using the voltage across one lamp in a series of four on 500 volts direct current. It may be said for this instrument that after standing over two months in the power-house between tests, the constant had changed less than two-thirds of one per cent.

During the tests one terminal of the testing transformer was connected to the three leads from the armature winding and the other terminal to the frame and to ground. The measuring instruments were connected in the grounded side as far as possi-

ble. The temperature of the windings was taken by means of a thermometer near the floor line of the machine. Loss measure-

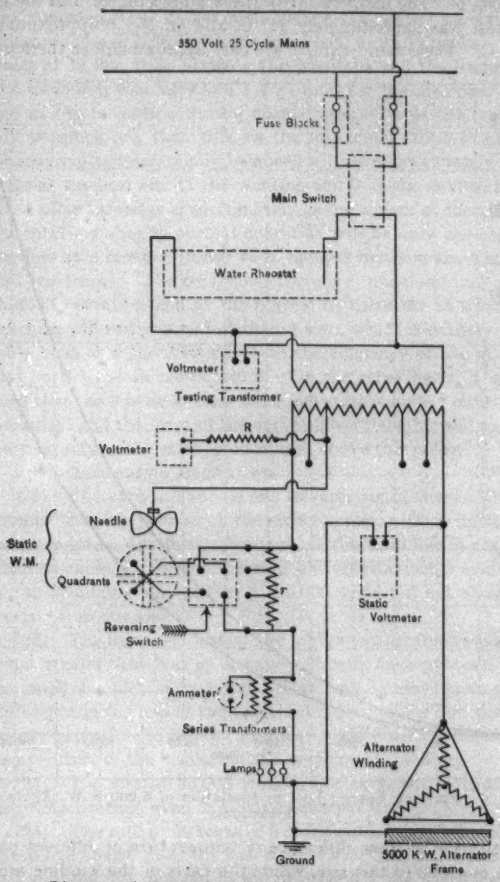

FIG. 3.—Diagram of Connections for Measurement of Insulation Losses of 5,000 K.W. Alternator Armatures.

ments were made at approximately 5,000, 10,000, 15,000, 20,000 and 25,000 volts.

The accompanying curves, Fig. 4, show the results of these measurements. Curve A was taken on alternator No. 7 and B on No. 6. The temperature of the windings on No. 7 at the time of test was approximately 21° C. and on No. 6 approximately 31° C. These temperatures are only approximate as there must

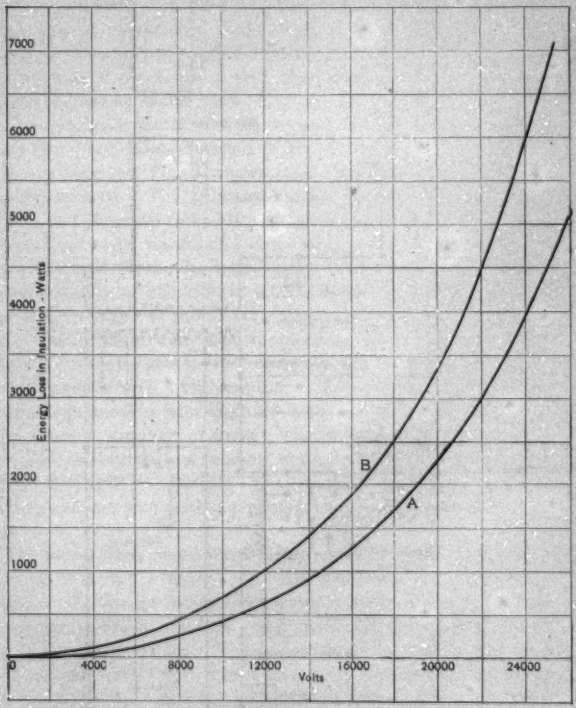

FIG. 4.—Showing Energy Loss in Insulation of 5,000 K.W. Alternator Armatures.

necessarily be some difference in temperature in different parts of a machine of this size, where the parts of the winding are so widely separated from each other. Unfortunately, it was not found feasible to make tests on one machine at different temperatures, and even if this had been done, it would have been

difficult to make accurate measurements of the temperature, for the reasons stated above.

The amount of insulating material under stress in these tests was approximately 19,500 cubic inches, this giving a maximum measured loss of 0.35 watts per cubic inch at 25,000 volts. At a stress of 11,000 volts between the windings and the frame, the loss measured was less than 1 k.w. total for the machine. The loss in the insulation during normal operation of the machine will be much less than this, as the maximum stress to ground when circuits are statically balanced will be approximately 6,400 volts at the lead end of the winding and 0 at the neutral point. As the loss increases approximately as the square of the voltage, the total loss due to normal operation will be only one-third of the loss at a stress of 6,400 volts applied between the windings and the frame. The total loss, therefore, under normal conditions of operation and at the normal temperature at which the machine will run will be less than ½ k.w., which is entirely negligible both as regards its effect on the efficiency of the machine and on the rise in temperature. On the other hand, it will be seen that the loss at a stress of 25,000 volts is a very measurable quantity, and the form of the curve shows that this will increase very rapidly as the stress is increased above this point.

From these curves we may see:

(22) The variation in loss due to variation of stress is slightly greater than the square of the stress applied. This increase in rate cannot be due to temperature, as the total loss is not sufficient to cause appreciable heating, and measurements made during a 30-minute application of 25,000 volts did not show any variation in the loss.

(23) The increased loss at the higher temperature was somewhat greater than was to be expected from measurements made on small samples of material. This may be due to an actual difference in the loss of the two machines or to the fact that it is nearly impossible to get any accurate measurement of the average temperature of the insulation of a machine of this size.

(24) The loss at 25,000 volts is not sufficient to cause any injurious heating, even in a long-continued test.

(25) The rate of increase of loss indicates that at a point not far above 25,000 volts the loss would be sufficient to cause heating and possible damage to the insulation if the stress were applied for any considerable length of time.

It is not possible to state in general terms the safe limiting

stress which can be applied in a time test to a piece of high potential apparatus, but measurements of the loss and a knowledge of the materials used will give the designer some idea for any particular machine. Such tests are very rarely necessary and should not be required on ordinary commercial apparatus. When a time test is required, it should be at a voltage much below the dielectric strength of the insulation under test.

In conclusion, the author wishes to state that while the work already done has been considerable, there is much more to be done in this line and it is hoped that many of the points now more or less obscure and uncertain may be cleared up in the near future. There are yet many materials to be investigated and experimenters who have the time and patience will find this a fertile field for their labors.

Finally, I wish to acknowledge my indebtedness to my coworkers, Mr. P. H. Thomas and Mr. Miles Walker, for much data and many valuable suggestions in connection with the investigation of this subject; the former particularly in connection with the extensive calorimeter tests carried out by him and the interpretation of their results, and the latter in connection with various temperature and wattmeter measurements. I am also indebted to Mr. H. G. Stott, Superintendent of Motive Power of the Manhattan Railway Company, for the facilities placed at my disposal for making the measurements on the 5,000 k.w. alternators in the above company's power-house.

REPORT OF THE COMMITTEE ON STANDARDIZATION

—o—

[Adopted at the 19th Annual Convention
at Great Barrington, Mass., June 20, 1902.]

—o—

To the Council of The American Institute of Electrical Engineers.

Gentlemen:

Your Committee on Standardization begs to submit the following revised series of recommendations, which embraces the Committee's report of 1899, amended in view of such suggestions and extensions as experience and practice have since indicated to be desirable.

The subjects discussed in these recommendations are such as call for extension and revision from time to time, in view of the rapid advance of electrical engineering.

Yours respectfully,

FRANCIS B. CROCKER, *Chairman.*
A. E. KENNELLY.
JOHN W. LIEB, Jr.
C. O. MAILLOUX.
CHARLES P. STEINMETZ.
LEWIS B. STILLWELL.
ELIHU THOMSON.

GENERAL PLAN.

EFFICIENCY. Sections 1 to 24.

(I)	Commutating Machines,	Sections	7–10
(II)	Synchronous Machines,	"	11–12
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(V)	Stationary Induction Apparatus,	"	19–20
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APPENDICES.
(I) Efficiency.
(II) Apparent Efficiency.
(III) Power Factor and Inductance Factor.
(IV) Notation.
(V) Table of Sparking Distances.

PRELIMINARY DEFINITIONS:

A direct current is a unidirectional current.

A continuous current is a steady, or non-pulsating, direct current.

An alternating current is a current of equal half-waves in successively opposite directions.

An oscillating current is a current alternating in direction, and of decreasing amplitude.

Electrical Apparatus will be treated under the following heads:

I. COMMUTATING MACHINES, which comprise a constant magnetic field, a closed-coil armature, and a multi-segmental commutator connected thereto.

Under this head may be classed the following: Continuous-current generators; continuous-current motors; continuous-current boosters; motor-generators; dynamotors; converters and closed-coil arc machines.

A booster is a machine inserted in series in a circuit to change its voltage, and may be driven either by an electric motor, or otherwise. In the former case it is a motor-booster.

A motor-generator is a transforming device consisting of two machines; a motor and a generator, mechanically connected together.

A dynamotor is a transforming device combining both motor and generator action in one magnetic field, with two armatures, or with an armature having two separate windings.

For converters, see III.

II. SYNCHRONOUS MACHINES, which comprise a constant magnetic field, and an armature receiving or delivering alternating currents in synchronism with the motion of the machine; *i. e.*, having a frequency equal to the product of the number of pairs of poles and the speed of the machine in revolutions per second.

III. SYNCHRONOUS COMMUTATING MACHINES:—These include: 1. Synchronous converters, commonly called "converters"; *i. e.*, converters from alternating to direct, or from direct to alternating current, and 2. Double-current generators; *i. e.*, generators producing both direct and alternating currents.

A converter is a machice employing mechanical momemtum in changing electric energy from one form into another.

A converter may be either:

a. A direct-current converter, converting from a direct current to a direct current, or

b. A synchronous converter, formerly called a rotary converter, converting from an alternating to a direct current, or vice-versa.

Phase converters are converters from an alternating-current system to an alternating-current system of the same frequency but in different phase.

Frequency converters are converters from an alternating-current system of one frequency to an alternating-current system of another frequency, with or without change in the number of phases.

IV. RECTIFYING MACHINES, OR PULSATING-CURRENT GENERATORS, which produce a unidirectional current of periodically varying strength.

V. STATIONARY INDUCTION APPARATUS, *i. e.*, stationary apparatus changing electric energy to electric energy through the medium of magnetic energy. These comprise:

a. Transformers, or stationary induction apparatus in which the primary and secondary windings are electrically insulated from each other.

b. Auto-transformers, also called compensators: *i. e.*, stationary induction apparatus in which part of the primary winding is used as a secondary winding; or conversely.

c Potential regulators, or stationary induction apparatus having a coil in shunt, and a coil in series with the circuit, so arranged that the ratio of transformation between them is variable at will.

These may be divided into the following types, or combinations thereof:

1. Compensator potential regulators, in which the number of turns of one of the coils is changed.

2. Induction potential-regulators, in which the relative positions of primary and secondary coils is changed.

3. Magneto potential-regulators, in which only the direction of the magnetic flux with respect to the coils is changed.

d. Reactors, or Reactance coils, formerly called choking coils; *i. e.*, stationary induction apparatus used to produce impedance or phase displacement.

VI. ROTARY INDUCTION APPARATUS, which consist of primary and secondary windings rotating with respect to each other. They comprise:

a. Induction motors.

b. Induction generators.

c. Frequency converters.

d. Rotary phase converters.

EFFICIENCY.

1. The 'efficiency" of an apparatus is the ratio of its net power output to its gross power input.[1]

2. The efficiency of all apparatus, except such as may be intended for intermittent service, should be either measured at, or reduced to, the temperature which the apparatus assumes under continuous operation at full rated load, referred to a room temperature of 25° C.

With apparatus intended for intermittent service, the efficiency should be determined at the temperature assumed under specified conditions.

3. Electric power should be measured at the terminals of the apparatus.

4. In determining the efficiency of alternating-current apparatus, the electric power should be measured when the current is in phase with the e.m.f., unless otherwise specified, except when a definite phase difference is inherent in the apparatus, as in induction motors, induction generators, frequency converters, etc.

1. An exception should be noted in the case of storage batteries or apparatus for storing energy in which the efficiency, unless otherwise qualified, should be understood at the ratio of the energy output to the energy intake in a normal cycle.

5. Mechanical power in machines should be measured at the pulley, gearing, coupling, etc., thus excluding the loss of power in said pulley, gearing or coupling, but including the bearing friction and windage. The magnitude of bearing friction and windage may be considered as independent of the load. The loss of power in the belt and the increase of bearing friction due to belt tension, should be excluded. Where, however, a machine is mounted upon the shaft of a prime mover, in such a manner that it cannot be separated therefrom, the frictional losses in bearings and in windage, which ought, by definition, to be included in determining the efficiency, should be excluded, owing to the practical impossibility of determining them satisfactorily. The brush friction, however, should be included.

Where a machine has auxiliary apparatus, such as an exciter, the power lost in the auxiliary apparatus should not be charged to the machine but to the plant consisting of machine and auxiliary apparatus taken together. The plant efficiency in such cases should be distinguished from the machine efficiency.

6. The efficiency may be determined by measuring all the losses individually, and adding their sum to the output to derive the input, or subtracting their sum from the input to derive the output. All losses should be measured at, or reduced to, the temperature assumed in continuous operation, or in operation under conditions specified. (See Sections 26 to 35.)

In order to consider the application of the foregoing rules to various machines in general use, the latter may be conveniently divided into classes as follows:

I. COMMUTATING MACHINES.—

7. In commutating machines the losses are:

a. Bearing friction and windage. (See Section 5.)

b. Molecular magnetic friction, and eddy currents in iron and copper, also $I^2 r$ losses in cross-connections of cross-connected armatures. These losses should be determined with the machine on open circuit, and at a voltage equal to the rated voltage $+ I r$ in a generator, and $- I r$ in a motor, where I denotes the current strength and r denotes the internal resistance of the machine. They should be measured at the correct speed and voltage, since they do not usually vary in any definite proportion to the speed or to the voltage.

c. Armature resistance losses, $I^2 r'$, where I is the current strength in the armature, and r' is the resistance between armature brushes, excluding the resistance of brushes and brush contacts.

d. Commutator brush friction.

e. Commutator brush-contact resistance. It is desirable to point out that with carbon brushes the losses (*d*) and (*e*) are usually considerable in low-voltage machines.

f. Field excitation. With separately excited fields, the loss of power in the resistance of the field coils alone should be considered. With shunt fields or series fields, however, the loss of power in the accompanying rheostat should also be included, the said rheostat being considered as an essential part of the machine, and not as separate auxiliary apparatus.

(*b*) and (*c*) are losses in the armature or "armature losses"; (*d*) and (*e*) "commutator losses"; (*f*) "field losses."

8. The difference between the total losses under load and the sum of the losses above specified, should be considered as "load losses" and are usually trivial in commutating machines of small field distortion. When the field distortion is large, as is shown by the necessity for shifting the brushes between no load and full load, or with variations of load, these load losses may be considerable, and should be taken into account. This applies especially to constant-current arc-light generators. In this case the efficiency may be determined either by input and output measurements, or the load losses may be estimated by the method of Section II.

9. Boosters should be considered and treated like other direct-current machines in regard to losses.

10. In motor-generators, dynamotors or converters, the efficiency is the electric output divided by the electric input.

II. SYNCHRONOUS MACHINES.—

11. In synchronous machines the output or input should be measured with the current in phase with the terminal e.m.f., except when otherwise expressly specified.

12. The losses in synchronous machines are:

a. Bearing friction and windage; see Sec. 5.

b. Molecular magnetic friction and eddy currents in iron, copper and other metallic parts. These losses should be determined at open circuit of the machine at the rated speed and at the rated voltage, $+ I r$ in a synchronous generator, $- I r$ in a synchronous motor, where I = current in armature, r = armature resistance. It is undesirable to compute these losses from observations made at other speeds or voltages.

These losses may be determined either by driving the machine by a motor, or by running it as a synchronous motor, and adjusting its fields so as to get minimum current input and measuring the input by wattmeter.

In the latter case, with polyphase machines, several wattmeters must be used, arranged so as to measure unbalanced load. The former method is preferable, since the latter is liable to error caused by acceleration and retardation due to a pulsation of frequency, or an inherent tendency to surging.

c. Armature-resistance loss, which may be expressed by $p I^2 r$; where r = resistance of one armature circuit or branch, I = the current in such armature circuit or branch, and p = the number of armature circuits or branches.

d. Load losses as defined in Section 8. While these losses cannot well be determined individually, they may be considerable and, therefore, their joint influence should be determined by observation. This can be done by operating the machine on short circuit and at full-load current, that is, by determining what may be called the "short-circuit core loss." With the low field intensity and great lag of current existing in this case, the load losses are usually greatly exaggerated.

One-third of the short-circuit core loss may, as an approximation, and in the absence of more accurate information, be assumed as the load loss.

e. Collector-ring friction and contact resistance. These are generally negligible, except in machines of extremely low voltage.

f. Field excitation. In separately-excited machines, the $I^2 r$ of the field coils proper should be used. In self-exciting machines, however, the loss in the field rheostat should be included. (See Section 7 *f*.)

III. SYNCHRONOUS COMMUTATING MACHINES.—

13. In converters, the power on the alternating-current side is to be measured with the current in phase with the terminal e.m.f., unless otherwise specified.

14. In double-current generators, the efficiency of the machine should be determined as a direct-current generator in accordance with Section 7 and as an alternating-current generator in accordance with Section 12. The two values of efficiency may be different, and should be clearly distinguished.

15. In converters the losses should be determined when driving the machine by a motor. These losses are:

a. Bearing friction and windage. (See Section 5).

b. Molecular magnetic friction and eddy currents in iron, copper and metallic parts, also $I^2 r$ loss, due to cross-current in cross-connected armatures. These losses should be determined at open circuit and at the rated terminal voltage, no allowance being made for the armature resistance

since the alternating and the direct currents flow in opposite directions.

c. Armature resistance. The loss in the armature is $q I^2 r$, where I = direct current in armature, r = armature resistance and q, a factor which is equal to 1.47 in single-circuit single-phase, 1.15 in double-circuit single-phase, 0.59 in three-phase, 0.39 in quarter-phase, and 0.27 in six-phase converters.

d. Load losses. The load losses should be determined in the same manner as described in Section 12 *d*, with reference to the direct-current side.

e and *f*. Losses in commutator and collector friction and brush contact resistance. (See Sections 7 and 12.)

g. Field excitation. In separately-excited fields, the $I^2 r$ loss in the field coils proper should be taken, while in shunt and series fields the rheostat loss should be included, except where fields and rheostats are intentionally modified to produce effects outside of the conversion of electric power, as for producing phase displacement for voltage control. In this case 25 per cent. of the $I^2 r$ loss in the field proper at non-inductive alternating circuit should be added as proper estimated allowance for normal rheostat losses. (See Section 7 *f*.)

16. Where two similar synchronous machines are available, their efficiency can be determined by operating one machine as a converter from direct to alternating, and the other as a converter from alternating to direct, connecting the alternating sides together, and measuring the difference between the direct-current input, and the direct-current output. This process may be modified by returning the output of the second machine through two boosters into the first machine and measuring the losses. Another modification is to supply the losses by an alternator between the two machines, using potential regulators.

IV. Rectifying Machines or Pulsating-Current Generators.—

17. These include: Open-coil arc machines, constant-current rectifiers, constant-potential rectifiers.

The losses in open-coil arc machines are essentially the same as in Sections 7 to 10 (closed-coil commutating machines). In this case, however, the load losses are usually greater, and the efficiency should be measured by input-and-output test, using wattmeters for measuring the output. In alternating-current rectifiers, the output must be also measured by wattmeter and not by voltmeter and ammeter, since owing to the pulsation of current and e.m.f., a considerable discrepancy may exist between watts and volt-amperes, amounting to as much as 10 or 15 per cent.

18. In constant-current rectifiers, transforming from constant-potential alternating to constant direct current, by means of constant-current transforming devices and rectifying commutators, the losses in the transformers are to be included in the efficiency, and have to be measured when operating the rectifier, since in this case the losses are generally greater than when feeding an alternating secondary circuit. In constant-current transforming devices, the load losses may be considerable, and, therefore, should not be neglected.

The most satisfactory method of determining the efficiency in rectifiers is to measure electric input and electric output by wattmeter. The input is usually inductive, owing to a considerable phase displacement and to wave distortion. For this reason the apparent efficiency should also be considered, since it is usually much lower than the true efficiency. The power consumed by the synchronous motor or other source driving the rectifier should be included in the electric input.

V. Stationary Induction Apparatus.—

19. Since the efficiency of induction apparatus depends upon the wave shape of e.m.f., it should be referred to a sine wave of e.m.f., except where expressly specified otherwise. The efficiency should be measured with

non-inductive load, and at rated frequency, except where expressly specified otherwise. The losses are:

a Molecular magnetic friction and eddy currents measured at open circuit and at rated voltage — $I\,r$, where I = rated current, r = resistance of primary circuit.

b. Resistance losses, the sum of the $I^2\,r$ in the primary and in the secondary windings of a transformer, or in the two sections of the coil in a compensator or auto-transformer, where I = current in the coil or section of coil. r = resistance.

c. Load losses, *i. e.*, eddy currents in the iron and especially in the copper conductors, caused by the current. They should be measured by short-circuiting the secondary of the transformer and impressing upon the primary an e.m.f. sufficient to send full-load current through the transformer. The loss in the transformer under these conditions measured by wattmeter gives the load losses + $I^2\,r$ losses in both primary and secondary coils.

d. Losses due to the methods of cooling, as power consumed by the blower in air-blast transformers, and power consumed by the motor driving pumps in oil or water cooled transformers. Where the same cooling apparatus supplies a number of transformers or is installed to supply future additions, allowance should be made therefor.

20. In potential regulators, the efficiency should be taken at the maximum voltage for which the apparatus is designed, and with non-inductive load, unless otherwise specified.

VI. ROTARY INDUCTION APPARATUS.—

21. Owing to the existence of load losses, and since the magnetic density in the induction motor under load changes in a complex manner, the efficiency should be determined by measuring the electric input by wattmeter, and the mechanical output at the pulley, gear, coupling, etc.

22. The efficiency should be determined at the rated frequency, and the input measured with sine waves of impressed e.m.f.

23. The efficiency may be calculated from the apparent input, the power factor, and the power output. The same applies to induction generators. Since phase displacement is inherent in induction machines, their apparent efficiency is also important.

24. In frequency converters, *i.e.*, apparatus transforming from an alternating system to an alternating system of different frequency, with or without a change in the number of phases, and in phase converters, *i. e.*, apparatus converting from an alternating system, usually single-phase, to another alternating system, usually polyphase, of the same frequency, the efficiency should also be determined by measuring both output and input.

VII. TRANSMISSION LINES.—

25. The efficiency of transmission lines should be measured with non-inductive load at the receiving end, with the rated receiving pressure and frequency, also with sinusoidal impressed e.m.f.'s, except where expressly specified otherwise, and with the exclusion of transformers or other apparatus at the ends of the line.

RISE OF TEMPERATURE.

GENERAL PRINCIPLES.—

26. Under regular service conditions, the temperature of electrical machinery should never be allowed to remain at a point at which permanent deterioration of its insulating material takes place.

27. The rise of temperature should be referred to the standard conditions of a room-temperature of 25°C., a barometric pressure of 760 mm.

and normal conditions of ventilation; that is, the apparatus under test should neither be exposed to draught nor enclosed, except where expressly specified.

28. If the room temperature during the test differs from 25° C., the observed rise of temperature should be corrected by $\frac{1}{2}$ per cent. for each degree C. Thus with a room temperature of 35° C., the observed rise of temperature has to be decreased by 5 per cent., and with a room temperature of 15° C., the observed rise of temperature has to be increased by 5 per cent. The thermometer indicating the room temperature should be screened from thermal radiation emitted by heated bodies, or from draughts of air. When it is impracticable to secure normal conditions of ventilation on account of an adjacent engine, or other sources of heat, the thermometer for measuring the air temperature should be placed so as fairly to indicate the temperature which the machine would have if it were idle, in order that the rise of temperature determined shall be that caused by the operation of the machine.

29. The temperature should be measured after a run of sufficient duration to reach practical constancy. This is usually from 6 to 18 hours, according to the size and construction of the apparatus. It is permissible, however, to shorten the time of the test by running a lesser time on an overload in current and voltage, then reducing the load to normal, and maintaining it thus until the temperature has become constant.

In apparatus intended for intermittent service, as railway motors, starting rheostats, etc., the rise of temperature should be measured after operation under as nearly as possible the conditions of service for which the apparatus is intended, and the conditions of the test should be specified.

In apparatus which by the nature of their service may be exposed to overload, as railway converters, and in very high voltage circuits, a smaller rise of temperature should be specified than in apparatus not liable to overloads or in low voltage apparatus. In apparatus built for conditions of limited space, as railway motors, a higher rise of temperature must be allowed.

30. In electrical conductors, the rise of temperature should be determined by their increase of resistance where practicable. For this purpose the resistance may be measured either by galvanometer test, or by drop-of-potential method. A temperature coefficient of 0.42 per cent. per degree C., from and at 0° C., may be assumed for copper.[2] Temperature elevations measured in this way are usually in excess of temperature elevations measured by thermometers.

When thermometers are applied to the free surface of a machine, it is desirable that the bulb of the thermometer should be covered by a pad of definite area. A convenient pad may be formed of cotton waste in a shallow circular box about one and a half inches in diameter, through a slot in the side of which the thermometer bulb is inserted. An unduly large pad over the thermometer tends to interfere with the natural liberation of heat from the surface to which the thermometer is applied.

31. With apparatus in which the insulating materials have special heat-resisting qualities, a higher temperature elevation is permissible.

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2. By the formula

$$R_t = R_0 (1 + 0.0042\, t) \text{ and } R_{t+\theta} = R_0 [1 + 0.0042\, (t + \theta)]$$

where R_t is the initial resistance at room temperature t° C.

$R_{t+\theta}$ is the final resistance at temperature elevation θ° C.

R_0 is the inferred resistance at 0° C.

These combine into the formula

$$\theta = (238.1 + t) \left(\frac{R_{t+\theta}}{R_t} - 1 \right) \quad \text{degrees C.}$$

32. In apparatus intended for service in places of abnormally high temperature, a lower temperature elevation should be specified.

33. It is recommended that the following maximum values of temperature elevation should not be exceeded:

Commutating machines, rectifying machines and synchronous machines
Field and armature, by resistance, 50° C.
Commutator and collector rings and brushes, by thermometer, 55° C.
Bearings and other parts of machine, by thermometer, 40° C.
Rotary induction apparatus:
Electric circuits, 50° C., by resistance
Bearings and other parts of the machine 40° C., by thermometer.
In squirrel-cage or short-circuited armatures, 55° C., by thermometer, may be allowed.
Transformers for continuous service—electric circuits by resistance 50° C., other parts by thermometer, 40° C., under conditions of normal ventilation.
Reactors, induction- and magneto-regulators—electric circuits by resistance 50° C., other parts by thermometer 40° C.
Where a thermometer, applied to a coil or winding, indicates a higher temperature elevation than that shown by resistance measurement, the thermometer indication should be accepted. In using the thermometer, care should be taken so to protect its bulb as to prevent radiation from it, and, at the same time, not to interfere seriously with the normal radiation from the part to which it is applied.

34. In the case of apparatus intended for intermittent service, except railway motors, the temperature elevation which is attained at the end of the period corresponding to the term of full load, should not exceed 50° C., by resistance in electric circuits. In the case of transformers intended for intermittent service, or not operating continuously at full load, but continuously in circuit, as in the ordinary case of lighting transformers, the temperature elevation above the surrounding air-temperature should not exceed 50° C. by resistance in electric circuits and 40° C. by thermometer in other parts, after the period corresponding to the term of full load. In this instance, the test load should not be applied until the transformer has been in circuit for a sufficient time to attain the temperature elevation due to core loss. With transformers for commercial lighting, the duration of the full-load test may be taken as three hours, unless otherwise specified. In the case of railway, crane and elevator motors, the conditions of service are necessarily so varied that no specific period corresponding to the full-load term can be stated.

35. The commercial rating of a railway motor should be the h.p. output giving 75° C. rise of temperature, above a room temperature of 25° C. after one hour's continuous run at 500 volts terminal pressure, on a stand, with the motor covers removed.

For determining the service temperature of a railway motor, the temperature rise should be determined by operating the motor on a straight and level track and under specified conditions:

(1). As to the load carried in tons per motor.
(2). The schedule speed in miles per hour.
(3). The number of stops per mile.
(4). The duration in seconds of the stops.
(5). The acceleration to be developed in miles per hour per second.
(6). The braking retardation to be developed in miles per hour per second.

These specifications should be determined, or agreed upon, as equivalent to the actual service, and the motors to be closed or open, according to the way in which they are to be operated in service.

The tests should be made in both directions over the same track.

By a " level track " should be understood a track in which the gradient does not exceed one-half per cent. at any point.

By a "straight track" should be understood a track in which the radius of curvature is nowhere less than the distance travelled by the car in 30 seconds, at the maximum speed reached during the run.

The wind velocity during a test should not exceed 10 miles per hour in any direction.

INSULATION.

36. The ohmic resistance of the insulation is of secondary importance only, as compared with the dielectric strength, or resistance to rupture by high voltage.

Since the ohmic resistance of the insulation can be very greatly increased by baking, but the dielectric strength is liable to be weakened thereby, it is preferable to specify a high dielectric strength rather than a high insulation resistance. The high-voltage test for dielectric strength should always be applied.

INSULATION RESISTANCE.—

37. Insulation resistance tests should, if possible, be made at the pressure for which the apparatus is designed.

The insulation resistance of the complete apparatus must be such that the rated voltage of the apparatus will not send more than $\frac{1}{1,000,000}$ of the full load current, at the rated terminal voltage, through the insulation. Where the value found in this way exceeds 1 megohm, 1 megohm is sufficient.

DIELECTRIC STRENGTH.—

38. The dielectric strength or resistance to rupture should be determined by a continued application of an alternating e.m.f. for one minute. The source of alternating e.m.f. should be a transformer of such size that the charging current of the apparatus as a condenser does not exceed 25 per cent. of the rated output of the transformer.

39. In alternating-current apparatus, the test should be made at the frequency for which the apparatus is designed.

40. The high-voltage tests should not be applied when the insulation is low, owing to dirt or moisture, and should be applied before the machine is put into commercial service.

The high potential test should be made at the temperature consumed under normal operation, as specified in Paragraph 2 under "Efficiency."

41. It should be pointed out that tests at high-voltages considerably in excess of the normal voltages, to determine whether specifications are fulfilled, are admissible on new machines only.

42. The test for dielectric strength should be made with the completely assembled apparatus and not with its individual parts, and the voltage should be applied as follows:[1]

1st. Between electric circuits and surrounding conducting material, and

2d. Between adjacent electric circuits, where such exist, as in transformers.

The tests should be made with a sine wave of e.m.f., or where this is not available, at a voltage giving the same striking distance between needle points in air, as a sine wave of the specified e.m.f., except where expressly specified otherwise. As needles, new sewing needles should be used. It is recommended to shunt the apparatus during the test by spark gap of needle points set for a voltaga exceeding the required voltage by 10 per cent.

A table of approximate sparking distances is given in Appendix V.

43. The following voltages are recommended for apparatus not including transmission lines or switchboards:

1. [NOTE.—This Section (No. 42), was referred back by the Convention to the Committee with power to amend, and may be subsequently revised.—EDITOR.

Rated Terminal Voltage.			Rated Output.	Testing Voltage.
Not exceeding	400 volts		Under 10 k.w.	1,000 volts.
" " "			10 k.w. and over	1,500 "
400 and over, but less than		800 volts	Under 10 k.w.	1,500 "
" " "		"	10 k.w. and over	2,000 "
800 "		1,200 "	Any	3,500 "
1,200 "		2,500 "	Any	5,000 "
2,500 "		10,000 "	Any	Double the normal rated voltages.
10,000 "		20,000 "	Any	10,000 volts above normal rated voltages.
20,000 "			Any	50 % above normal rated voltages.

Except that transformers of 5,000 volts or less, directly feeding consumption circuits, should be tested at 10,000 volts.

Synchronous motor fields and fields of converters started from the alternating current side ..... 5,000 volts.

Alternator field circuits should be tested under a breakdown test voltage corresponding to the rated voltage of the exciter, and referred to an output equal to the output of the alternator; *i. e.*, the exciter should be rated for this test as having an output equal to that of the machine it excites.

Condensers should be tested at twice their rated voltage and at their rated frequency.

The values in the table above are effective values, or square roots of mean square, reduced to a sine wave of e.m.f.

44. In testing insulation between different electric circuits, as between primary and secondary of transformers, the testing voltage must be chosen corresponding to the high-voltage circuit.

45. In transformers of 20,000 volts upwards, it should be sufficient to test the transformer by operating it at 50 per cent. above its rated voltage; if necessary, with sufficiently higher frequency to induce this voltage.

46. The test of the insulation of a transformer, if no testing transformer is available, may be made by connecting one terminal of the high-voltage winding to the core and low-voltage winding, and then repeating the test with the other terminal of the high-voltage winding so connected. The test of dielectric resistance between the low voltage winding and the core should be in accordance with the recommendation in Section 43, for similar voltages and capacities.

47. High voltage tests on transformers or other apparatus should be based upon the voltages between the conductors of the circuit to which they are connected.

48. When machines or apparatus are to be operated in series, so as to employ the sum of their separate e.m.f.'s, the voltage should be referred to this sum, except where the frames of the machines are separately insulated both from ground and from each other.

The insulation between machines and between each machine and ground should be tested, the former referred to the voltage of one machine, and the latter to the total voltage of the series.

49. Underground cables, and line switches, should be tested by the application of an alternating e.m.f. for one minute at twice the voltage at which the cable or switch is to be operated.

REGULATION.

50. The term regulation should have the same meaning as the term "inherent regulation," at present frequently used.

51. The regulation of an apparatus intended for the generation of constant potential, constant current, constant speed, etc., is to be measured by the maximum variation of potential, current, speed, etc., occurring within the range from full-load to no-load, under such constant conditions

of operation as give the required full-load values, the condition of full-load being considered in all cases as the normal condition of operation.

52. The regulation of an apparatus intended for the generation of a potential current, speed, etc., varying in a definite manner between full load and no load, is to be measured by the maximum variation of potential current, speed, etc., from the satisfied condition, under such constant conditions of operation as give the required full-load values.

If the manner in which the variation in potential, current, speed, etc., between full-load and no-load is not specified, it should be assumed to be a simple linear relation; *i. e.*, undergoing uniform variation between full load and no-load.

The regulation of an apparatus may, therefore, differ according to its qualification for use. Thus, the regulation of a compound-wound generator specified as a constant-potential generator, will be different from that it possesses when specified as an over-compounded generator.

53. The regulation is given in percentage of the full-load value of potential, current, speed, etc., and the apparatus should be steadily operated during the test under the same conditions as at full load.

54. The regulation of generators is to be determined at constant speed, of alternating apparatus at constant impressed frequency.

55. The regulation of a generator-unit, consisting of a generator united with a prime-mover, should be determined at constant conditions of the prime mover; *i. e.*, constant steam pressure, head, etc. It would include the inherent speed variations of the prime-mover. For this reason the regulation of a generator-unit is to be distinguished from the regulation of either the prime-mover, or of the generator contained in it, when taken separately.

56. In apparatus generating, transforming or transmitting alternating currents, regulation should be understood to refer to non-inductive load, that is to a load in which the current is in phase with the e.m.f. at the output side of the apparatus, except where expressly specified otherwise.

57. In alternating apparatus receiving electric power, regulation should refer to a sine wave of e.m.f., except where expressly specified otherwise.

58. In commutating machines, rectifying machines and synchronous machines, as direct-current generators and motors, alternating-current and polyphase generators, the regulation is to be determined under the following conditions:

a. At constant excitation in separately excited fields.
b. With constant resistance in shunt field circuits, and
c. With constant resistance shunting series fields; *i. e.*, the field adjustment should remain constant, and should be so chosen as to give the required full-load voltage at full-load current.

59. In constant-potential machines, the regulation is the ratio of the maximum difference of terminal voltage from the rated full-load value (occurring within the range from full load to open circuit) to the full-load terminal voltage.

60. In constant-current apparatus, the regulation is the ratio of the maximum difference of current from the rated full-load value (occurring within the range from full-load to short-circuit, or minimum limit of operation), to the full-load current, at constant speed; or, in transformers, etc., at constant impressed voltage and frequency.

61. In constant-power apparatus, the regulation is the ratio of maximum difference of power from the rated full-load value (occurring within the range of operation specified) to the rated power.

62. In over-compounded machines, the regulation is the ratio of the maximum difference in voltage from a straight line connecting the no-load and full-load values of terminal voltage as function of the current, to the full-load terminal voltage.

63. In constant-speed continuous-current motors, the regulation is the

ratio of the maximum variation of speed from its full-load value (occurring within the range from full-load to no-load) to the full-load speed.

64. In constant-potential non-inductive transformers, the regulation is the ratio of the rise of secondary terminal voltage from full-load to no-load (at constant primary impressed terminal voltage) to the secondary terminal voltage.

65. In induction motors, the regulation is the ratio of the rise of speed from full-load to no-load (at constant impressed voltage), to the full-load speed.

The regulation of an induction motor is, therefore, not identical with the slip of the motor, which is the ratio of the drop in speed from synchronism, to the synchronous speed.

66. In converters, dynamotors, motor-generators and frequency-converters, the regulation is the ratio of the maximum difference of terminal voltage at the output side from the rated full-load voltage (at constant impressed voltage and at constant frequency), to the full-load voltage on the output side.

67. In transmission lines, feeders, etc., the regulation is the ratio of maximum voltage difference at the receiving end, between no-load and full non-inductive load, to the full-load voltage at the receiving end, with constant voltage impressed upon the sending end.

68. In steam engines, the regulation is the ratio of the maximum variation of speed in passing from full-load to no-load (at constant steam pressure at the throttle) to the full-load speed.

69. In a turbine or other water-motor, the regulation is the ratio of the maximum variation of speed from full-load to no-load (at constant head of water; *i. e.*, at constant difference of level between tail race and head race), to the full-load speed.

70. In alternating-current apparatus, in addition to the non-inductive regulation, the impedance ratio of the apparatus should be specified; *i. e.*, the ratio of the voltage consumed by the total internal impedance of the apparatus at full-load current, to its rated full-load voltage. As far as possible, a sinusoidal current should be used.

71. When in synchronous machines the regulation is computed from the terminal voltage and impedance voltage, the exciting ampere-turns corresponding to terminal voltage plus armature-resistance-drop, and the ampere-turns at short-circuit corresponding to the armature-impedance-drop, should be combined vectorially to obtain the resultant ampere-turns, and the corresponding internal e.m.f. should be taken from the saturation curve.[1]

VARIATION AND PULSATION —

72. In prime movers which do not give an absolutely uniform rate of rotation or speed, as in steam engines, the "variation" is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution as 360°; and the pulsation is the ratio of the maximum change of speed in an engine cycle to the average speed.

73. In alternators or alternating-current circuits in general, the variation is the maximum difference in phase of the generated wave of e.m.f. from a wave of absolutely constant frequency, expressed in degrees, and is due to the variation of the prime mover. The pulsation is the ratio of the maximum change of frequency during an engine cycle to the average frequency.

74. If n = number of poles, the variations of an alternator is $n/2$ times the variation of its prime-mover if direct connected, and $n/2p$ times the variation of the prime-mover if rigidly connected thereto in the velocity ratio p.

1. [NOTE.—This Section (No. 71), was referred back by the Convention to the Committee with power to amend, and may be subsequently revised.

RATING.

75. Both electrical and mechanical power should be expressed in kilowatts, except when otherwise specified. Alternating-current apparatus should be rated in kilowatts on the basis of non-inductive condition; *i. e.*, with the current in phase with the terminal voltage.

76. Thus the electric power generated by an alternating-current apparatus equals its rating only at non-inductive load, that is, when the current is in phase with the terminal voltage.

77. Apparent power should be expressed in kilovolt-amperes as distinguished from real power in kilowatts.

78. If a power-factor other than 100 per cent. is specified, the rating should be expressed in kilovolt-amperes and power-factor, at full load.

79. The full-load current of an electric generator is that current which with the rated full-load terminal voltage gives the rated kilowatts, but in alternating-current apparatus only at non-inductive load.

80. Thus, in machines in which the full-load voltage differs from the no-load voltage, the full-load current should refer to the former.

If P = rating of an electric generator and E = full-load terminal voltage, the full load current is:

$I = \frac{P}{E}$ in a continuous-current machine or single-phase alternator.

$I = \frac{P}{E\sqrt{3}}$ in a three-phase alternator.

$I = \frac{P}{2E}$ in a quarter-phase alternator.

81. Constant-current machines, such as series arc-light generators, should be rated in kilowatts based on terminal volts and amperes at full load.

82. The rating of a fuse or circuit breaker should be the current-strength which it will continually carry. In addition thereto, the current strength of which it will open the circuit should be specified.

CLASSIFICATION OF VOLTAGES AND FREQUENCIES.—

83. In direct-current, low-voltage generators, the following average terminal voltages are in general use and are recommended:

125 volts. 250 volts. 550 to 600 volts.

84. In direct-current and alternating-current low-voltage circuits, the following average terminal voltages are in general use and are recommended:

110 volts. 220 volts.

In direct-current power circuits, for railway and other service, 500 volts may be considered as standard.

85. In alternating-current, constant-potential, primary-distribution circuits, an average e.m.f. of 2,200 volts, with step-down transformers of ratios 1/10 and 1/20, is in general use, and is recommended.

86. In alternating-current, constant-potential, high-pressure circuits, at the receiving end, the following voltages are in general use, and are recommended:

6,000. 10,000. 15,000. 20,000. 30,000. 40,000. 60,000.

87. In alternating-current generators, or generating systems, a range of terminal voltage should be provided from no-load voltage to 10 per cent. in excess thereof, to cover drop in transmission. If a greater range than ten per cent. is specified, the generator should be considered as special.

88. In alternating-current circuits, the following approximate frequencies are recommended as desirable:

25 ~ 60 ~ 120 ~[3]

These frequencies are already in extensive use and it is deemed advisable to adhere to them as closely as possible.

OVERLOAD CAPACITIES.—

89. All guarantees on heating, regulation, sparking, etc., should apply to the rated load, except where expressly specified otherwise, and in alternating-current apparatus to the current in phase with the terminal e.m.f., except where a phase displacement is inherent in the apparatus.

90. All apparatus should be able to carry the overload specified in Section 92, without self-destruction by heating, sparking, mechanical weakness, etc., and with an increase in temperature elevation not exceeding 15° C., above those specified for full loads, the overload being applied after the apparatus has acquired the temperature corresponding to full-load continuous operation. (See Sections 30 to 34.)

91. Overload guarantees should refer to normal conditions of operation regarding speed, frequency, voltage, etc., and to non-inductive conditions in alternating apparatus, except where a phase displacement is inherent in the apparatus.

92. The following overload capacities are recommended:

1st. In direct-current generators and alternating-current generators; 25 per cent. for two hours.

2d. In direct-current motors, induction motors and synchronous motors, not including railway motors and other apparatus intended for intermittent service, 25 per cent. for two hours, and 50 per cent. for one minute, for momentary overload capacity.

3d. Synchronous converters. 50 per cent. for one-half hour.

4th. Transformers. 25 per cent. for two hours. Except in transformers connected to apparatus for which a different overload is guaranteed, in which case the same guarantees shall apply for the transformers as for the apparatus connected thereto.

5th. Exciters of alternators and other synchronous machines, 10 per cent. more overload than is required for the excitation of the synchronous machine at its guaranteed overload, and for the same period of time.

7th. All exciters of alternating-current, single-phase or polyphase generators should be able to give at constant speed, sufficient voltage to excite the alternator, at the rated speed, to the full load terminal voltage, at the rated output in kilovolt-amperes and with 50 per cent. power factor.

LUMINOUS SOURCES.—

93. It is customary in industrial practice at the present time to rate incandescent lamps upon the basis of their mean horizontal candle-power; but in comparing sources of light in which the relative distribution of luminosity differs considerably, the comparison should be based upon the total quantity of light, or total flux of light emitted by each source.

94. The mean spherical intensity of a luminous source is its total flux of light, expressed in lumens, divided by 4π. If the mean spherical intensity be expressed in British candles, the flux of light will be in British-candle-lumens (B. C. Lumens). If the mean spherical intensity be expressed in Hefners, the flux of light will be expressed in Hefner-lumens (H. Lumens).

95. The efficiency of a luminous source should be defined as the ratio of the light it emits to the power it consumes. In the case of an incandescent lamp, this ratio might be expressed in B. C. Lumens per watt at lamp terminals.

3. The frequency of 120~ may be considered as covering the already existing commercial frequencies between 120~ and 140~.

96. The specific consumption of a lamp should be the reciprocal of its efficiency, or the watts per B. C. Lumen.

97. The consumption per horizontal candlepower of a lamp is the ratio of power consumed at terminals to the mean horizontal candlepower, or watts per mean horizontal candlepower.

98. The Hefner-Alteneck amyl-acetate lamp is, in spite of its unsuitable color, the standard luminous source generally used in accurate photometric measurements. In comparing lamps with this standard, the ratio of the horizontal intensities of the Hefner and British candles may be accepted conventionally as follows: 1 Hefner under Reichsanstalt standard conditions = 0.88 British candle.

APPENDIX I.

EFFICIENCY OF PHASE-DISPLACING APPARATUS.—

In apparatus producing phase displacement as, for example, synchronous compensators, exciters of induction generators, reactors, condensers, polarization cells, etc., the efficiency should be understood to be the ratio of the volt-ampere activity to the volt-ampere activity plus power loss.

The efficiency may be calculated by determining the losses individually, adding to them the volt-ampere activity, and then dividing the volt-ampere activity by the sum.

1st. In synchronous compensators and exciters of induction generators, the determination of losses is the same as in other synchronous machines under Sections 11 and 12.

2d. In reactive coils the losses are molecular friction, eddy losses and I^2r loss. They should be measured by wattmeter. The efficiency of reactive coils should be determined with a sine wave of impressed e.m.f., except where expressly specified otherwise. In reactive coils, the load losses may be considerable.

3d. In condensers, the losses are due to dielectric hysteresis and leakage, and should be determined by wattmeter with a sine wave of e.m.f.

4th. In polarization cells, the losses are those due to electric resistivity and a loss in the electrolyte of the nature of chemical hysteresis and are usually very considerable. They depend upon the frequency, voltage and temperature, and should be determined with a sine wave of impressed e.m.f., except where expressly specified otherwise.

APPENDIX II.

APPARENT EFFICIENCY.—

In apparatus in which a phase displacement is inherent to their operation, apparent efficiency should be understood as the ratio of net power output to volt-ampere input.

Such apparatus comprise induction motors, reactive synchronous converters, synchronous converters controlling the voltage of an alternating current system, self-exciting synchronous motors, potential regulators and open magnetic circuit transformers, etc.

Since the apparent efficiency of apparatus generating electric power depends upon the power factor of the load, the apparent efficiency, unless otherwise specified, should be referred to a load power-factor of unity.

APPENDIX III.

POWER FACTOR AND INDUCTANCE FACTOR.—

The power factor in alternating circuits or apparatus may be defined as the ratio of the electric power, in watts, to volt-amperes.

The inductance factor is to be considered as the ratio of wattless volt-amperes to total volt amperes.

Thus, if p = power factor, q = inductance factor.
then with a sine wave of e.m.f.

$$p^2 = q^2 = 1$$

The power factor is the

$$\frac{\text{(energy component of current or e.m.f.)}}{\text{(total current or e.m.f.)}} = \frac{\text{true power}}{\text{volt amperes.}}$$

and the inductance factor is the

$$\frac{\text{(wattless component of current or e.m.f.)}}{\text{(total current or e.m.f.)}}$$

Since the power-factor of apparatus supplying electric power depends upon the power-factor of the load, the power-factor of the load should be considered as unity, unless otherwise specified.

APPENDIX IV.

The following notation is recommended:

E, e, voltage, e.m.f., potential difference
I, i, current
P, power
φ, magnetic flux
$\mathfrak{B}$, magnetic density
R, r, resistance
x, reactance
Z, z, impedance
L, l, inductance
C, c, capacity
Y, y, admittance
b, susceptance
g, conductance.

Vector quantities when used should be denoted by capital italics.

APPENDIX V.

Table of Sparking Distances in Air between Opposed Sharp Needle-Points, for Various Effective Sinusoidal Voltages, in inches and in centimetres.

Kilovolts Sq. Root of Mean Square	Distance. Inches	Cms.	Kilovolts Sq. Root of Mean Square	Distance. Inches	Cms.
5	0.225	0.57	60	4.65	11.8
10	0.47	1.19	70	5.85	14.9
15	0.725	1.84	80	7.1	18.0
20	1.0	2.54	90	8.35	21.2
25	1.3	3.3	100	9.6	24.4
30	1.625	4.1	110	10.75	27.3
35	2.0	5.1	120	11.85	30.1
40	2.45	6.2	130	12.95	32.9
45	2.95	7.5	140	13.95	35.4
50	3.55	9.0	150	15.0	38.1

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 20th, 1902.

THE DETERMINATION OF ALTERNATOR CHARACTERISTICS.

BY LOUIS A. HERDT.

The exacting requirements now to be met in regard to the performance of A. C. machinery and the expense of duplicating in the testing room all the conditions of future operations, make proper indirect methods for the determination of the characteristics of A. C. apparatus of great value.

In the following discussion the e.m.f. induction and current relations under different conditions as to load and power factor in the armatures of several types of A. C. generators will be considered both theoretically and experimentally, and indirect methods for obtaining the regulation of a particular machine developed and applied to those of other types.

For convenience of reference the following divisions have been made:

Armature reaction and armature reactance.
Tests of an inductor alternator.
Alternator regulation, indirect methods for determination.
Application to inductor machine.
Application to other types.

Armature Reaction and Armature Reactance.

Consider the no-load induction distribution on an alternator of the type shown in Fig. 1, structural details of which are given in Fig. 5. During the rotation of the inductor the armature induction pulsates between a maximum and minimum value, but is constant in direction. When an inductor lug is exactly

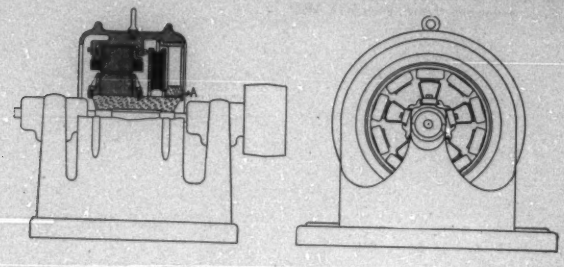

FIG 1

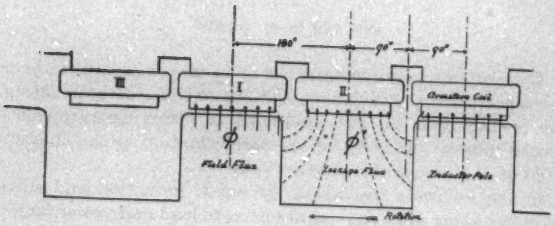

FIG. 2

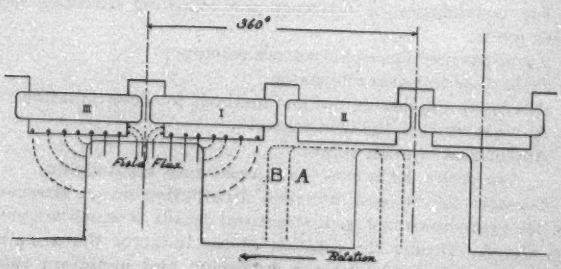

FIG. 3.

opposite an armature coil (see Fig. 2), the induction through that coil is a maximum, but as the lug recedes from it, the induction diminishes to a minimum, until the lug stands opposite the adjacent coil. The minimum induction is a leakage flux and the e.m.f. of the machine is diminished in proportion to the ratio of this minimum induction to its maximum value. This leakage flux should, therefore, be as small as possible.

The average e.m.f. induced in any armature coil is the difference between the flux φ, shown in Fig. 2, which passes through that coil when covered by an inductor lug, and the flux φ', when

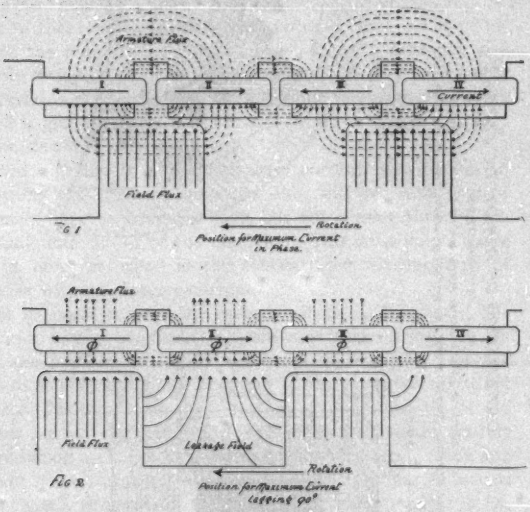

FIG. 4.

the coil is midway between these two adjacent lugs, divided by the time of half a period, that is:

$$\varepsilon_{\text{average}} = (\varphi - \varphi') \div (T/2)$$

Fig. 3 will be referred to later.

When the armature carries a current, the effective magnetic flux is the resultant of the m.m.f. of the field and of the armature ampere turns. If the armature current lags by 90° the field and armature m.m.f.'s will exactly oppose each other, as shown in Diagram 2, Fig. 4.

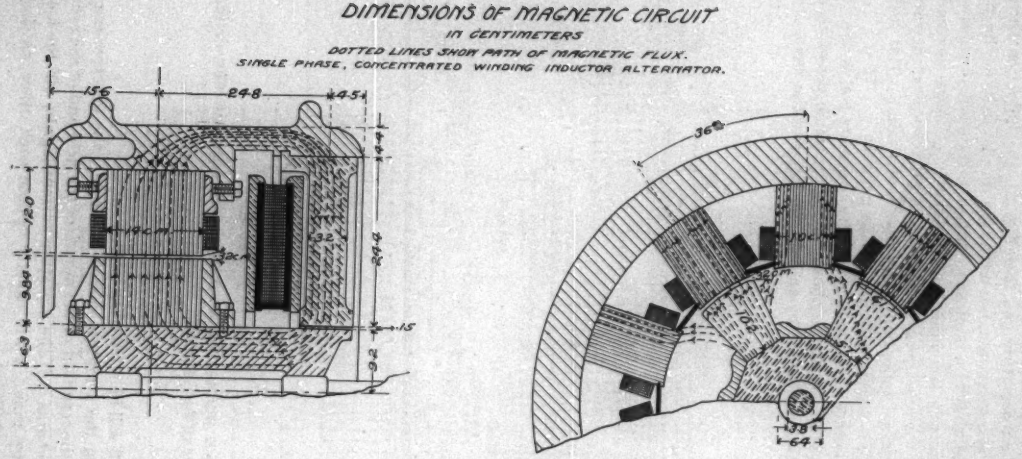
DIMENSIONS OF MAGNETIC CIRCUIT
IN CENTIMETERS
DOTTED LINES SHOW PATH OF MAGNETIC FLUX.
SINGLE PHASE, CONCENTRATED WINDING INDUCTOR ALTERNATOR.
156
248
45
120
38
63
244
15
9
36
10
38
64

FIG. 5.

If n and i are respectively the number of turns and amperes in field coils, and N and I the number of turns and the effective current in one armature coil, the resultant m.m.f. of field and armature will be:

$$(n\,i - N\,I\sqrt{2}) \text{ for coil 1.}$$

and $$(n\,i + N\,I\sqrt{2}) \text{ for coil 2.}$$

As seen, the m.m.f.'s of coils 1 and 3 directly oppose the field m.m.f., diminishing the maximum induction, while the action of coil 2 is to increase the leakage flux.

Both of these actions diminish the induced e.m.f. The reluctance of the path of the coils is, however, very different; the magnetic circuit of coil 1 is that of the machine and varies with the saturation of the machine circuit, while the magnetic circuit of coil 2 is made up largely of air and the flux through it is proportional to the armature current.

The m.m.f. due to this quadrature current, in addition to diminishing the effective armature flux, will generate lines of force encircling the armature coils, but not passing through the main magnetic circuit of the machine. This cross-magnetizing effect is, however, small in the concentrated winding type of alternator with quadrature current.

With in-phase current the case, however, is different. The diminution of effective flux (see position of inductor lug, Fig. 3), unless the machine is highly saturated, is negligible, for the m.m.f. of coils 1, and 2 (see Diagram 1, Fig. 4) tends only to set up a cross flux increasing the induction of the leading tip of the inductor lug and diminishing the induction through the trailing tip, producing a change in the distribution of magnetic flux and resultant wave form, but altering little the resultant induction or total e.m.f. generated. It is thus seen that the effect of the armature current in diminishing the total effective induction and varying its distribution depends on the phase relation of e.m.f. and current.

In considering the path presented to the armature flux at any angular position of the coils relatively to the inductor lugs, other than the particular ones just given, it will be seen that its reluctance periodically changes. As before stated, with the inductor lug opposite an armature coil (position A, Fig. 3), the reluctance of the magnetic of the armature coils is that of the machine, but after a small angular displacement of the inductor (position B,

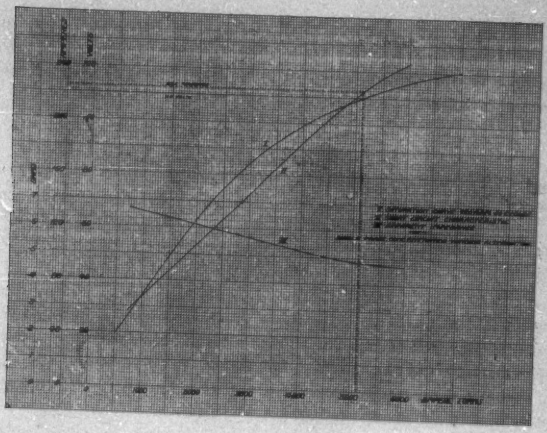

FIG. 6.

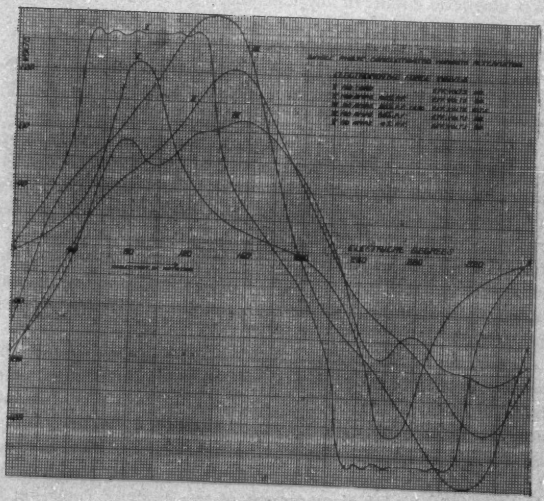

FIG. 7.

Fig. 3), the reluctance is diminished, the flux due to armature current increasing and becoming a purely local one. This periodic fluctuation of the reluctance in the path of the induction set up by the armature m.m.f., as easily seen, may have a very marked effect on the regulation and wave form of machines of the type illustrated.

Test of an Inductor Alternator.

The machine is that illustrated in Fig. 1. The magnetic dimensions are given in Fig. 5. The armature consists of ten coils of 75 turns each, connected in parallel, the resistance cold equals .04 ohms. The excitation is effected by a single exciting coil, as seen, containing 1,710 turns. The normal output is 15.4 k.w.; voltage, 110; speed, 720 r.p.m.

The following tests were made:

Saturation curve, 60 cycles.

Short circuit characteristic, 60 cycles.

Real induced e.m.f. waves, with different armature currents and different power factors, 3 amperes field excitation.

Current waves under different conditions.

Curves showing variation of induction due to armature current, for different positions of the inductor lug, 3 amperes field excitation.

From these were deduced curves of synchronous impedance, curves of induction distribution under different conditions of load, and curves, which for the present, we will call counter e.m.f. waves. Curve I, Fig. 6, is the saturation curve. Curve II is the short circuit characteristic. Curve III is the synchronous impedance, calculated. Curve 1, Fig. 7, is the no-load or nominal induced e.m.f. wave. Curve II is the real induced e.m.f. wave for inphase current of 140 amperes. The great variation in the induction distribution with the resultant change of wave form will be noticed. Curve III, Fig. 7, is the real induced e.m.f. wave for a leading current of 90 amperes, 95% power factor. Owing to the fact that with this particular power factor the armature current (Curve III, Fig. 8) is in step with the nominal induced e.m.f., the total effective induction has been but slightly altered in amount, as seen by Curve II, Fig. 9; its distribution, however, has been changed.

Curve IV, Fig. 7, is the real induced e.m.f. wave for 140 amperes, 88% power factor, lagging, and clearly shows the effect of diminishing power factor in bringing the real induced e.m.f. wave back in phase with the nominal induced e.m.f

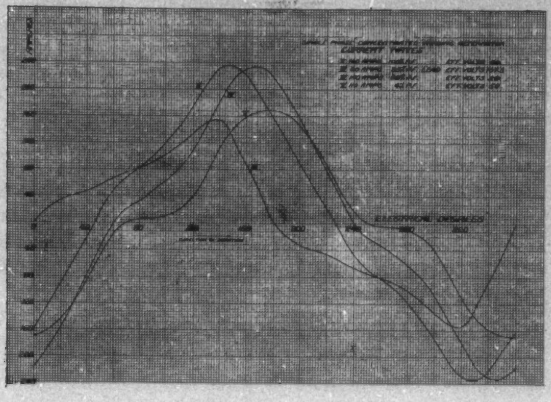

FIG. 8.

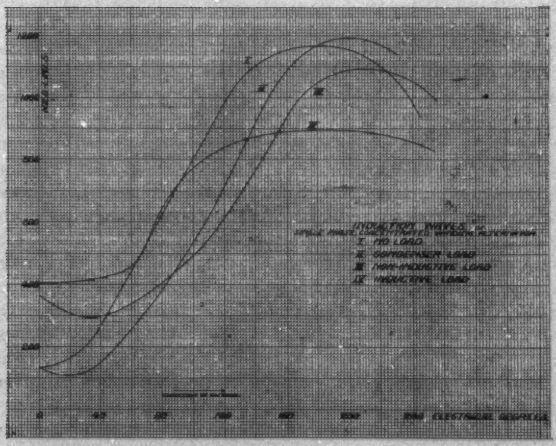

FIG. 9.

Curve V is the real induced e.m.f. wave for 110 amperes, 4% power factor, lagging. Here the e.m.f. wave, while greatly altered in extent and form, has returned almost exactly to, and in phase relation with, the nominal induced e.m.f., as, of course, would be expected. All the above e.m.f. waves were taken with a constant field excitation of three amperes and a speed of 720 r.p.m.

Curves II, III, IV and V, or curves of real induced e.m.f. waves under different conditions, were taken from a test coil of 75 turns, wrapped uniformly about an armature coil, and they equal the machine terminal e.m.f. waves plus the armature ohmic drop. For e.m.f. wave measurements a special contact maker was used, charging and discharging a condenser through a Weston voltmeter.

The tremendous change of wave form with character of load in this machine will be noted to be far too much for successful commercial use, but for purposes of illustration the machine is an excellent one.

Curves II, III, IV and V, Fig. 8, are current waves corresponding to the e.m.f. waves II, III, IV and V, Fig. 7. The shift of current with the nature of load shows clearly the change of the armature m.m.f. from a cross-magnetizing to a demagnetizing effect, as the lag increases from zero to 90°.

Curves I, II, III, and IV, Fig. 9, show the variation of induction through one armature coil with different positions of inductor lug, for armature currents (Fig. 8) of zero amperes, 90 amperes, 95% power factor, leading; 140 amperes, 100 % power factor; and 110 amperes, 4% power factor, lagging. These curves were determined by integrating the areas of the real induced e.m.f. waves, Curves I, II, III and V, Fig. 7.

By Curve I it will be noticed that the maximum induction in one armature coil is slightly over 1,160,000 lines, representing a maximum induction per square centimetre of about 10,000 lines. The minimum induction, or leakage flux, occurring when the armature coil is midway between two adjacent inductor lugs, is 130,000 lines.

Curve II is the induction wave with 90 amperes armature current, 95% power factor, leading. This current, as before stated, being in step with the nominal induced e.m.f., the maximum and minimum values of the induction through any of the armature coils is but slightly altered by the armature current, but the shift of the induction wave, due to the cross-magnetizing effect of the armature m.m.f., is easily seen.

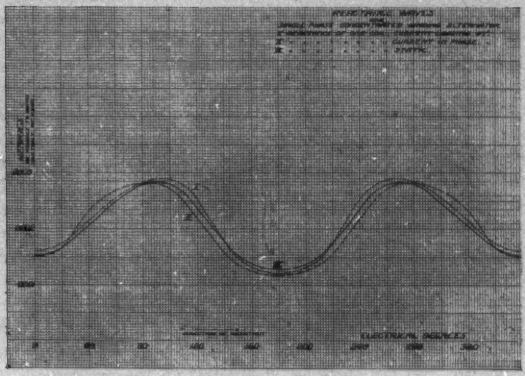

FIG. 10.

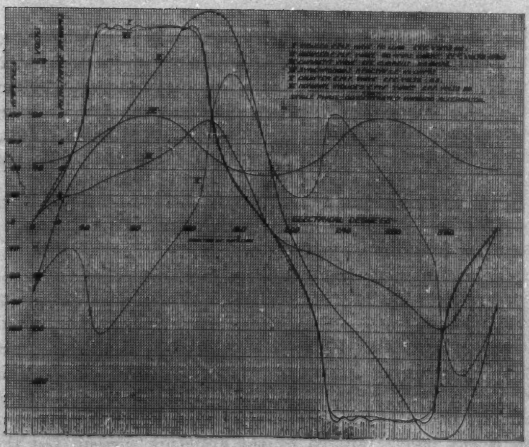

FIG. 11

Curve III is the induction wave corresponding to a current of 140 amperes in step with the terminal voltage, but lagging behind the nominal induced e.m.f. by nearly 50°, due to the armature reactance. The demagnetizing effect of the armature current now becomes marked, the maximum induction being diminished and the leakage flux increased.

Curve IV is the induction wave for 110 amperes, lagging 85° behind the nominal induced e.m.f. This curve shows with great clearness the demagnetizing effect of wattless armature currents, and the virtual absence of any cross-magnetizing effect. The maximum no-load induction is reduced from 1,160,000 lines to approximately 900,000 lines, and the no-load leakage is increased from 130,000 to 400,000 lines.

The shape of the induction wave is altered, becoming flatter, and its maximum and minimum values are changed, but it has regained a practically in-phase angular relation to the no-load induction wave. The diminution of voltage with quadrature current is thus seen to be due almost entirely to armature reaction.

From the above induction waves and from the instantaneous values of armature current, given in Fig. 8, the total induction due to the armature m.m.f. diminution of field flux, increase of stray field and cross lines for different positions of the inductor, are readily found.

If π is the increase or decrease of induction through the coil for any position of the inductor above or below the induction when no armature current is flowing, and if π be divided by the instantaneous value of the current and by 10^8, the result will be the total inductance of the coil in henrys, and multiplying by the angular velocity and the number of turns in the armature coil, we have the instantaneous value of the total inductance of the coil in ohms. This includes both the effective armature reaction and armature reactance. In Fig. 10 are given Curves I and II of total armature reactance calculated as above. Curve I is for non-inductive external load. Curve II is for current in phase with the nominal induced e.m.f.

These curves of inductance or reactance were also experimentally determined as follows:

A search coil of 75 turns was wound over one of the armature coils and connected to a suitable ballistic galvanometer. The fields were excited by a current of three amperes; different direct currents were passed through the armature for different posi-

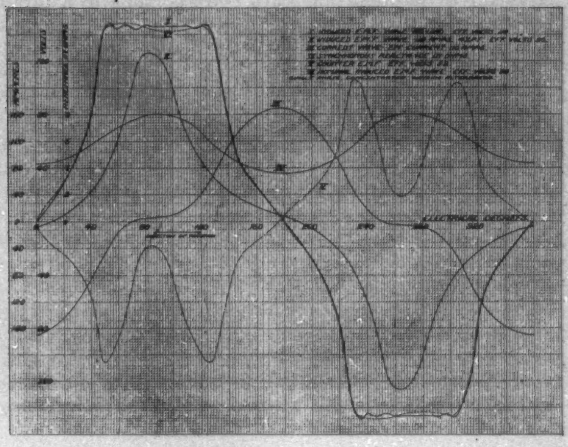

FIG. 12

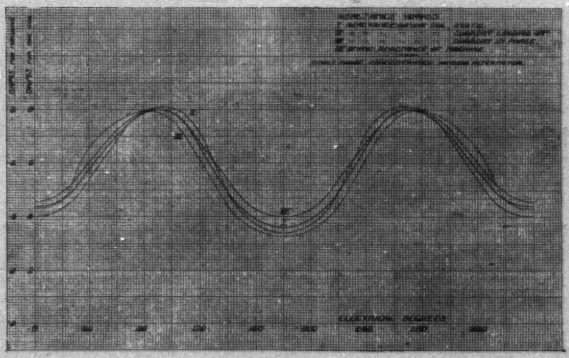

FIG. 13.

tions of the inductor lugs, and the throw of the galvanometer noted when the armature current was made or broken. Knowing the galvanometer constant, its readings indicated the total actual change in the number of lines threading the armature coils for different values of current and position of inductor.

Curve III, Fig. 10, gives the result in henrys when 100 amperes in the armature circuit was used, and is seen to correspond very closely to the values of reactance determined from the induction and current curves. A variation of armature current from a few amperes to 140 amperes gave virtually identical results.

The above curves of Fig. 10 show the variation of the total armature reactance for different positions of the inductor lug. The maximum reactance occurs when the inductor lug or pole is midway between two coils (2, Fig. 4); the minimum value when the inductor lugs are opposite armature coils (1, Fig. 4). The total armature reactance is thus seen to pulsate synchronously with the position of the inductor, maximum and minimum value occurring for inductor positions as above shown.

From the curves of total armature inductance with inductor position and armature current, the counter e.m.f., or e.m.f. which must be added to the real induced e.m.f. to give the nominal induced e.m.f., may be determined. Calling the counter e.m.f. at any instant, e, we have $e = (d\,L\,i) \div (dt - 10^{-8}) = (1) \div (10^{-8})\ [(L\,d\,i) \div (dt) + (i\,d\,L) \div (dt)]$ volts. Where L is the instantaneous value of the total inductance per coil taken from Curve III, Fig. 10, and i the instantaneous value of the current in the coil, taken from current waves, Fig. 8.

The method is then simply to take the sum of any instantaneous value of L into the slope of the current wave corresponding to such value, and the instantaneous value of i corresponding to L into the slope of the inductance wave at the same time. This divided by 10^{-8} will give the instantaneous value of the counter e.m.f. of the coil. The process is a tedious one, but by plotting the curves to a large scale, quite accurate results may be obtained.

Applying the method to the case where the armature current is in phase with the nominal induced e.m.f., we have the results shown in Fig. 11. Curve I is the no-lead or nominal induced e.m.f. wave experimentally determined. Curve II is the real induced e.m.f. wave with 90 amperes and external power factor of 95% leading. Both these curves are the same as shown in

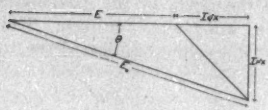

FIG. A.

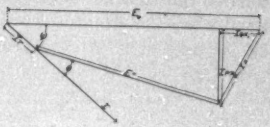

FIG. B.

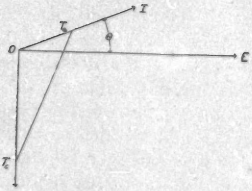

FIG. C.

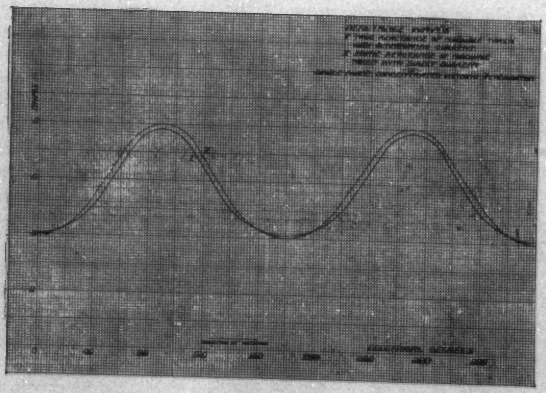

FIG. 14.

Fig. 7. Curve III is current wave, Curve IV the reactance wave and Curve V is the c.e.m.f. wave calculated from the equation as given above. Adding Curves V and II we have Curve VI, which should be identical with Curve I. Although not identical, the agreement between the two is extremely close.

If the equivalent sine wave or the c.e.m.f. wave is determined, it will be found to lag 90° behind the equivalent sine wave of the real induced e.m.f. wave. The effective value of the c.e.m.f. is 65 volts; the effective value of the nominal induced e.m.f. is 110 volts; and the effective value of the real induced e.m.f. is 107.5 volts, which together nearly form the right angled triangle that would be expected, as this c.e.m.f. is practically all due to the variation of induction set up by the cross-magnetizing currents of the armature. Dividing the effective value of the counter e.m.f. by the effective armature current, we have .722, a coefficient measuring the effect of cross-magnetization.

Applying the same method when the armature current lags by practically 90° behind the nominal induced e.m.f., we have the results given in Fig. 12. Curve I is as before the no-load or nominal e.m.f. wave. Curve II is the real induced e.m.f. with 110 amperes, lagging 85° from the nominal induced e.m.f. Curve III is the current wave; Curve IV the reactance wave; and Curve V the derived c.e.m.f. wave. Adding Curves II and V, as before, we have Curve VI, which again very closely corresponds to Curve I.

Determining the equivalent sine wave of the c.e.m.f., it will be seen to lag 90° behind the equivalent sine wave of current, but as the current lags practically 90° behind the nominal induced e.m.f., the c.e.m.f. wave is almost exactly in opposition to the nominal induced e.m.f., instead of being at 90° from it, as was the case with in-phase current. The effective value of the nominal induced e.m.f., is 110 volts; the effective value of the real induced e.m.f. is 50 volts; the effective value of the counter e.m.f. is 52 volts; this latter being virtually the difference between the first two. Dividing again the effective value of the counter e.m.f. by the armature current, we have .45, a coefficient now measuring the demagnetizing effect instead of the cross-magnetizing effect, as before.

It is thus seen that in this type of alternator, having a variable magnetic reluctance—and the statement is true for other types as well, as will be seen later—the e.m.f. vector representing the effective armature m.m.f., reaction and cross-magnetizing effect,

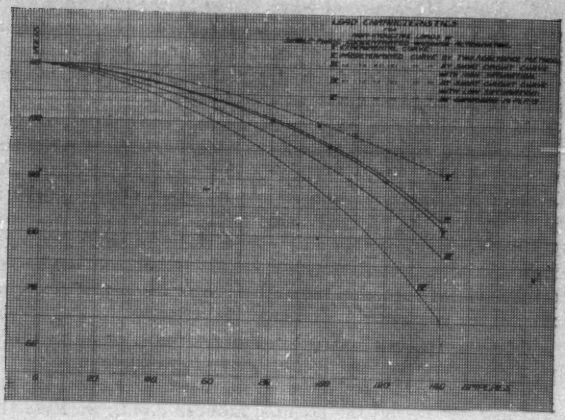

FIG. 15.

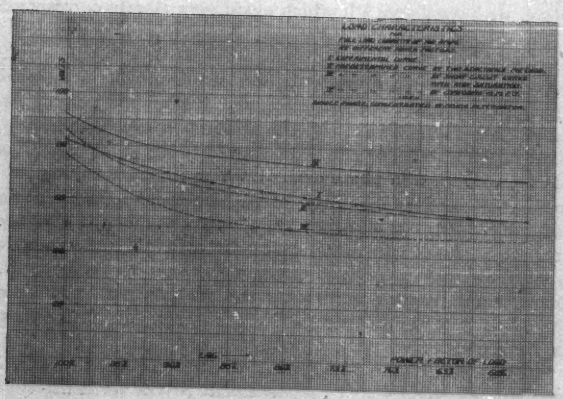

FIG. 16.

varies not only in magnitude but in angular relation to the nominal induced e.m.f. from 90° to 180°, as the power factor of the total circuit varies from unity to zero.

In Fig. 13 are given in ohms the inductance curves I, II and III of Fig. 10, reduced from henrys, and an additional curve, IV, giving in ohms the total inductance of the machine for different positions of the inductor lugs, the 10 armature coils being all in parallel. It will be noted that the adjacent minimum values for this latter curve are the same, and equal to one-tenth of the mean of the adjacent unequal minimum values of reactance for one coil, as a little consideration will show should be the case.

Alternator Regulation, Indirect Methods for Determination.

The term "synchronous reactance" has been very generally used as combining the effect of armature reaction and the stray field due to the cross-magnetizing effect of the armature current, in the determination of alternator regulation; and, properly measured as the resultant of the demagnetizing and cross-magnetizing armature m.m.f., will give correct results. But, in general, it cannot be determined as a result of a single observation, as is ordinarily assumed.

Usually the synchronous reactance is determined from the short-circuited characteristic at low, or comparatively low, field excitations, the method of procedure being to short-circuit the armature through an ammeter and vary the exciting current until full load armature current is reached. The value thus obtained, however, will be incorrect for the following reasons: The field excitation being much below normal, the quadrature armature current will have a much greater proportional demagnetizing effect than when the field is fully excited; and further, in general, the field due to the cross-magnetizing effect of an equal in-phase armature current is greater than the diminution of field flux to the quadrature current. If the latter were equal in a particular machine, and the synchronous reactance were determined with normal field excitation and full load quadrature current, its use would lead to correct results. If the demagnetizing effect of a given quadrature current is not equal to the cross-magnetizing effect of an equal in-phase current, as in general it is not, one may be determined as a function of the other, as will be shown below. The demagnetizing effect of varying quadrature armature currents with full field excitation

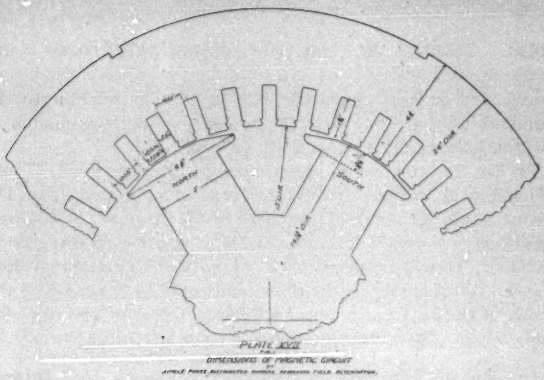

FIG. 17.

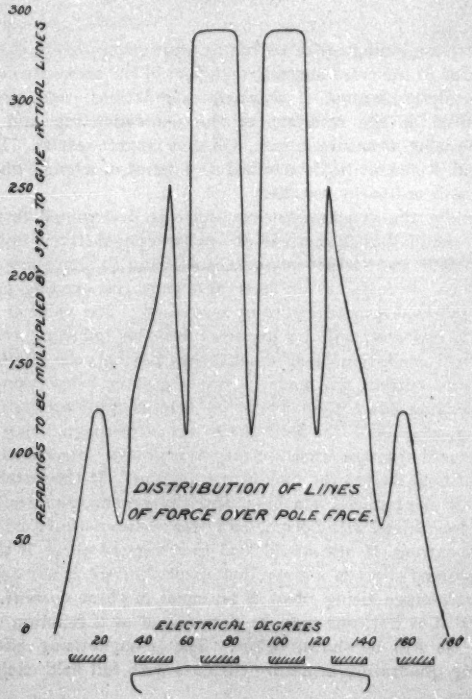

FIG. 17 b.

may be determined by working the alternator on a purely reactive load.

When the armature current lags behind the nominal induced e.m.f., by an angle between 0° and 90°, it may, of course, be regarded as made up of two components; the in-phase component, equal to the current multiplied by the cosine of the angle between the current and nominal induced e.m.f., and the quadrature component, equal to the current by the sine of the same angle.

Diagram *a* illustrates a method, which we will call the short-circuit characteristic method, used for the determination of alternator regulation. E is the terminal e.m.f., equal to the real induced e.m.f. when the armature ohmic drop is negligible. $I\,Q'\,x$ is taken as the component of the e.m.f. consumed by synchronous reactance corresponding to the demagnetizing effect of armature current. $I\,P'\,x$ is taken as the component of the e.m.f. consumed by synchronous reactance corresponding to the cross-magnetizing effect of armature current. x is the synchronous reactance determined from ordinary short-circuit characteristic with low field excitation; and P' and Q' are respectively the power factor and the inductance factor of the external load. From the diagram, we have:

$$E = \sqrt{E_0^2 - I^2 P'^2 x^2} - i\,Q'\,x$$

Applying this method to a given machine, it will generally be found to regulate better than the formula indicates, for the reason that the method of determining the magnetizing component of synchronous reactance gives too high a value for it. Other errors involved in the formula are the use of P', Q', as power and inductance factors of the load, instead of the power and inductance factors of the total circuit, armature and external load; and the assumption that the cross-magnetizing component of the synchronous reactance and demagnetizing component are equal.

Another approximate method, which we will call "composing m.m.f. method" (see *L'Industrie Electrique*, December, 1899), is illustrated in Diagram *c*. Referring to the figure, $O\,E$ is the real induced e.m.f.; $O\,I$, the current lagging by an angle θ behind the terminal volts. The armature ohmic drop is assumed to be negligible. On $O\,I$ is set off $O\,T_a$, the field m.m.f. necessary to overcome a quadrature current equal to I, determined from the

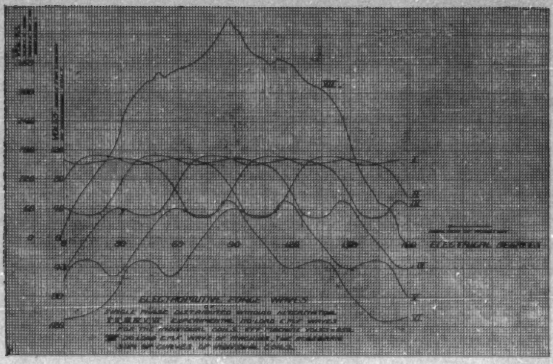

FIG. 18.

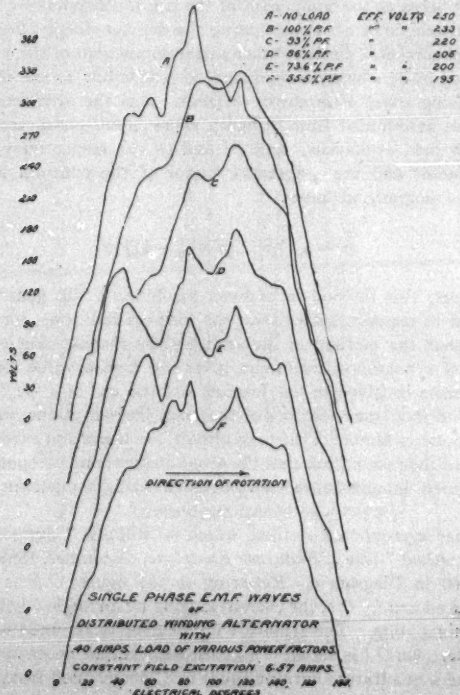
A- NO LOAD E.M.F. VOLTS 250
B- 100% P.F. " " 233
C- 93% P.F. " 220
D- 86% P.F. " 208
E- 73.6% P.F. " " 200
F- 35.5% P.F. " " 193
VOLTS
DIRECTION OF ROTATION
SINGLE PHASE E.M.F. WAVES
OF
DISTRIBUTED WINDING ALTERNATOR
WITH
40 AMPS. LOAD OF VARIOUS POWER FACTORS
CONSTANT FIELD EXCITATION 6.57 AMPS.
ELECTRICAL DEGREES

FIG. 19.

short-circuit characteristic. From T_a is struck an arc with a radius equal to the field m.m.f. The distance to the point where this arc intersects a line drawn at right angles to $O\,E$ is taken as the effective m.m.f., producing the real induced e.m.f., E. Having $O\,T_e$ or the effective m.m.f. acting, E is determined from the saturation curve. As will be readily appreciated, the principal objections to this method are the assumption that the alternator works on a straight line characteristic and the neglect of armature self-induction.

The following method, which we will call for convenience "the two reactance method," has been found to give accurate results when applied to a number of alternators of widely different types.

The demagnetizing effect of different quadrature currents is determined at full load field excitation, and not at an excitation just sufficient to circulate full load current through the armature on short-circuit, as is ordinarily done.

The armature, instead of being short-circuited, is operated at constant full load field excitation on a suitable variable reactance and the difference between the voltage given by the saturation curve and terminal voltage is noted. The voltage thus obtained divided by the current gives the value of the demagnetizing component of the synchronous reactance corresponding to normal conditions of machine operation. The cross-magnetizing effect for different in-phase currents is taken as equal to the demagnetizing component of the synchronous reactance multiplied by the ratio of the total inductance of the armature, with the inductor lugs in position shown in I, Fig. 3, to the inductance of the armature with the inductor lugs in the position shown in II, Fig. 3. The inductance is determined by passing through the armature, from external source, a suitable alternating current when the lugs are in the position just named, and the fields fully excited.

Curve I, Fig. 14, is a complete curve of armature reactance at 60 cycles with the inductor in the positions named and intermediate ones. The ratio of maximum to minimum values of this curve is the ratio referred to above.

Curve II, Fig. 14, is one obtained by the ballistic method, and is seen to agree quite closely with Curve I.

Using the values so obtained for the demagnetizing and cross-magnetizing components of synchronous reactance, the Diagram *b*, due to Blondel, properly expresses the relations of e.m.f. and currents in the armature of an alternator under full load condi-

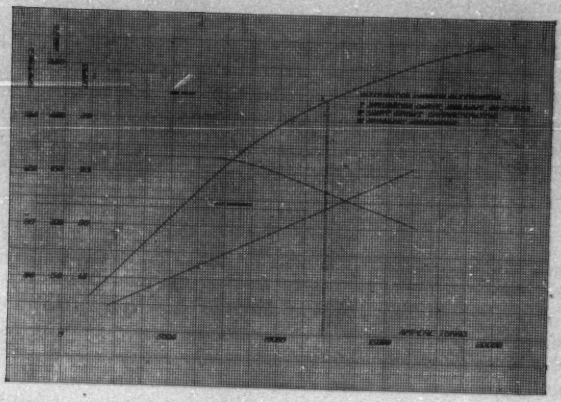

FIG. 20

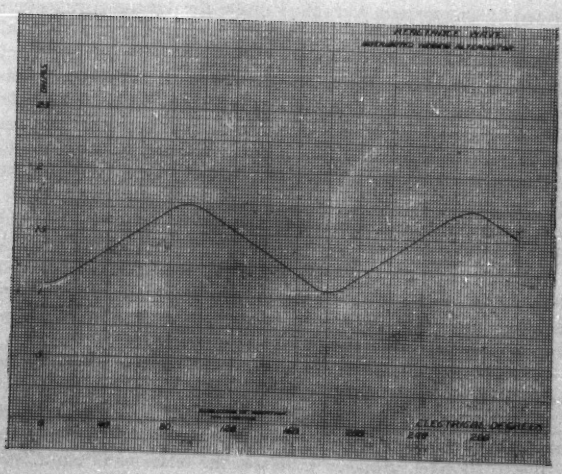

FIG. 21

tions of operation. E_0 is the nominal induced e.m.f.; φ, the phase angle between the current and the nominal induced e.m.f.; θ, the phase angle between the current and the terminal voltage; X, the demagnetizing component of synchronous reactance; X_2, the cross-magnetizing component of synchronous reactance; P and Q, respectively, the power and inductance factors of the whole circuit; $I r$,the ohmic drop; and E, the terminal e.m.f.

Application to Inductor Alternator.

The different indirect methods for determining the variation of terminal voltage as a function of the armature current and the power factor of the external load for constant field excitation, stated above, have been applied to the 15.4 k.w. inductor alternator, shown in Figs. 1 and 5, and compared with directly observed results.

The saturation curve, short-circuit characteristic, and the curve of synchronous impedance for this alternator were given in Fig. 6. Curve I, Fig. 15, gives the actual observed load characteristic for non-inductive load at a constant field excitation of 3 amperes.

Curve II is a calculated curve by the two reactance method. It is seen to agree exceedingly well with the observed curve.

Curve III is the calculated curve by the short-circuit characteristic method, using the value of the synchronous reactance obtained with full field excitation, the short-circuited armature current being 225 amperes, or 85 amperes above the normal full load current.

Curve IV is a calculated curve by the short-circuit characteristic method, using the value of the synchronous reactance obtained with a field excitation just sufficient to circulate the full load current of 140 amperes through the armature.

Curve V is the calculated curve by composing m.m.f.'s.

It will be noted that while the terminal voltage by the short-circuit method, for a given armature current, is much less than the observed terminal volts, the agreement becomes much more close when the values of the synchronous reactance are obtained with high field excitation. The method of composing m.m.f.'s gives much too high a value for the terminal voltage, as will be expected.

In Fig. 16 are shown the results of the same methods applied to the case of constant armature current with variable external

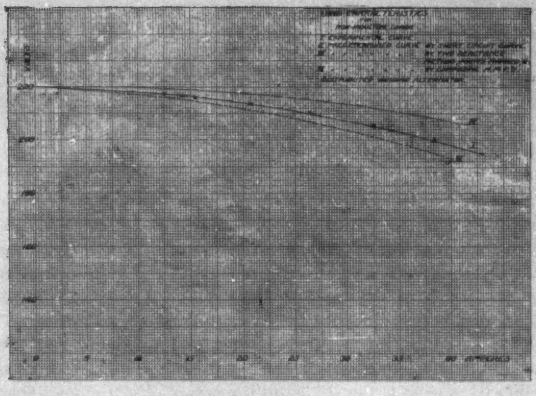

FIG. 22.

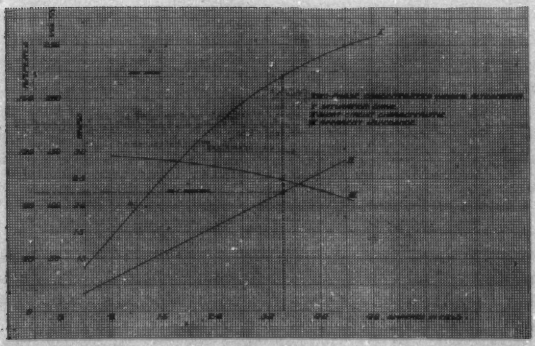

FIG. 24.

power factor, as compared with the observed results.

Curve I gives the observed values of the terminal e.m.f., with power factor, for constant field current of 3 amperes and constant armature current of 140 amperes. Curve II is that calculated by the two reactance method; Curve III by the short-circuit characteristic with high field excitation; and Curve IV by composing m.m.f.'s.

Again, the two reactance method is seen to give accurate results, while the short-circuit characteristic method gives, as before, too small values, and the method of composing m.m.f.'s too large values of the terminal e.m.f.

Application to other Types.

A second machine upon which a number of tests were made was of the revolving field, distributed armature winding type, the magnetic circuit of which is shown in *a*, Fig. 17.

In addition to the load characteristics observed and determined by the different methods, tests were made of the induction distribution under the different conditions; the wave form of the terminal e.m.f. was analyzed into its component wave forms, due to the individual armature coils; and the conditions affecting the change of wave form with character of load were studied.

In *b*, Fig. 17, is given the no load induction distribution with the field magnet in the position shown, the fields being excited to give normal terminal voltage. This was obtained by means of a ballistic galvanometer and suitable exploring coils in the usual way. It will be noted that the larger part of the induction enters the armature through the teeth, as might have been expected, but about one-third of the induction, in the case of the teeth immediately opposite the pole, passes into the armature by way of a slot due to the high induction intensity in the teeth.

Curves I, II, III, IV, V and VI, Fig. 18, are the individual e.m.f. waves for each of six successive angularly displaced armature coils in series, when the machine is connected as a single phaser. Curve VII is obtained by taking the algebraic sum of the instantaneous values of the first six curves, and agrees very closely with the no-load observed e.m.f. wave, Curve IV, Fig. 19. These curves show most clearly the advantages of distributed windings as regards wave form, for while the e.m.f. from an individual coil, as Curve IV, is a very flat topped wave, and somewhat similar to the no load e.m.f. wave of the concentrated winding inductor alternator (Curve I, Fig. 7), the machine

DIMENSIONS OF MAGNETIC CIRCUIT
OF
TWO-PHASE CONCENTRATED WINDING INDUCTOR ALTERNATOR.
DOTTED LINES SHOW PATH OF MAGNETIC FLUX.

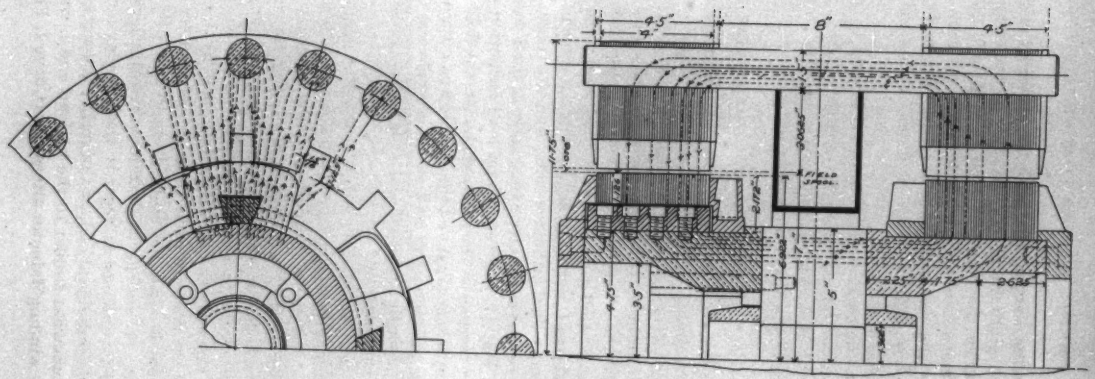

FIG. 23.

e.m.f. wave, which is the resultant of six such waves displaced by 30°, is very nearly sinusoidal.

If a machine is desired which will give not only an extremely close approximation to a sine wave e.m.f. at no load, but also shall hold such wave form with changes of the load, the number of slots per phase per pole must be made as large as practicable, and the induction distribution such that the e.m.f. waves for the individual armature coils are also as near to sine waves as possible.

In Fig. 19 are given a series of e.m.f. waves with constant field excitation, a constant full load armature current of 40 amperes, and power factors varying from unity to .55. It is to be noted that while the wave form changes with the power factor, the change is by no means so great as in the case of the concentrated winding inductor type.

Curve I, Fig. 20, is the saturation curve of the machine shown in Fig. 17; Curve II, the short-circuit characteristic; and Curve III, the synchronous impedance calculated from Curves I and II. At 4.6 amperes exciting current, the impedance is 2.6 ohms, the effective resistance being .186 ohms, the reactance 2.31 ohms.

The complete reactance wave for this machine, obtained by sending through the armature an alternating current, the field poles being in different positions, is shown in Fig. 21. The ratio of maximum to minimum values of the reactance is seen to be 1.625. As the demagnetizing component of synchronous reactance from the short-circuit characteristic is 2.31 ohms, the cross-magnetizing component of the reactance is $2.31 \times 1.625 = 3.75$ ohms.

The three indirect methods for the determination of alternator regulation before discussed, were applied to this machine and compared with the experimental curve. The results are shown in Fig. 22. Curve I is the experimental or observed load characteristic for a non-inductive external load. Curve II is calculated by the short-circuit characteristic method, high field excitation. Curve III, determined by the two reactance method, is identical with the experimental curve, Curve IV, determined by composing m.m.f.'s. The correspondence between the observed and calculated value by the two reactance method is highly satisfactory.

The magnetic circuit of the third machine tested is shown in Fig. 23. The machine is a 10 k.w., 220 volt, 60 cycle, two-phase

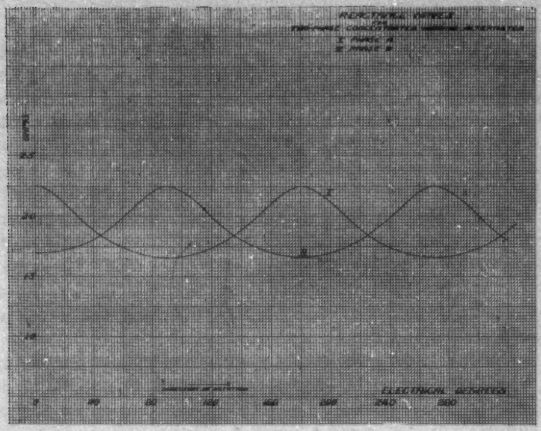

FIG. 25.

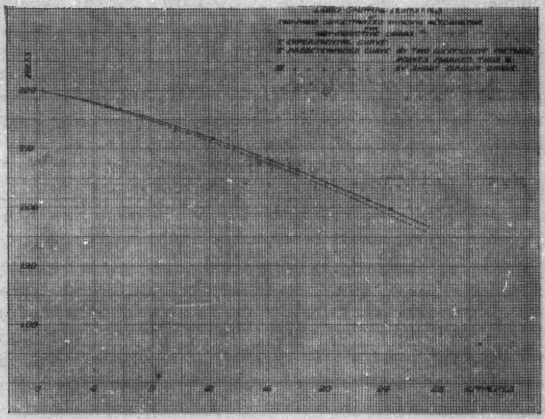

FIG. 26.

inductor alternator of well-known type, having concentrated armature winding. Curve I, Fig. 24, is the saturation curve; Curve II, the short-circuit characteristic; and Curve III, the synchronous impedance.

At 3.4 amperes exciting current the synchronous impedance is 2.46 ohms, the effective resistance, as found by independent measurements, .588 ohms, and hence the demagnetizing component of the synchronous reactance at full load field excitation is 2.37 ohms. The ratio of the armature reactance with the inductors midway between two adjacent armature coils, to the armature reactance with the inductors opposite the armature coils, as obtained from reactance waves, Fig. 25, is 1.3. The cross-magnetizing component of the synchronous reactance is, therefore, $2.37 \times 1.3 = 3.1$ ohms.

Curve I, Fig. 26, is the observed external characteristic with non-inductive load. Curve II, the points of which are exactly on Curve I, is the load characteristic determined by the two reactance method. Curve III is determined by the short-circuit characteristic method with high field excitation, and since in this machine the stray field due to the cross-magnetizing turns is less than one-third greater than the field set up by the demagnetizing turns for equal current, it agrees fairly closely with the observed results.

My thanks are due to Prof. R. B. Owens, whose suggestions and assistance made possible the investigation, and to Mr. H. A. Burson, Demonstrator in Electrical Engineering, for much help, both in the drawing of the curves and in the calculations, and also to Messrs. Franklin, Maxwell and Jackson, graduates of 1902, for taking observations.

McGill University,
Montreal, Can.,
June 9, 1902,

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 20th, 1902.

A NEW CURVE TRACING INSTRUMENT.

BY ROBERT B. OWENS.

For conveniently and accurately tracing current curves in circuits of small resistance and inductance without appreciably altering their time constants, the instrument illustrated in Fig. 1 was devised some years ago, but having subsequently proved generally useful as a laboratory instrument, a consideration of its characteristics may not be without interest.

In general appearance, it is similar to the ordinary differential galvanometer, with the exception that the usual suspended permanent magnet with attached mirror is replaced by a circular coil of fine wire supported by two thin phosphor-bronze suspensions. The bifilar method of suspension at once allows easy variation of sensibility and affords a means of introducing current into the movable coil. Fig. 2 shows the arrangement of the principal instrument parts in more detail.

The action of the instrument is as follows: The variable current of which a trace is desired is introduced into, say, the outer pair of the two concentric coils, a suitable direct current is sent into the inner pair of coils and a contact maker sends an impulse of current from a constant source of e.m.f. through the movable coil. If the D. C. current in the inner fixed coil is equal and opposite in magnetic effect to the instantaneous value of the variable current at time of contact, no deflection of the movable coil will be observed. If a deflection, however, does occur, the D. C. current is varied until such deflection becomes zero, then the D. C. current, as read by an ordinary Weston ammeter,

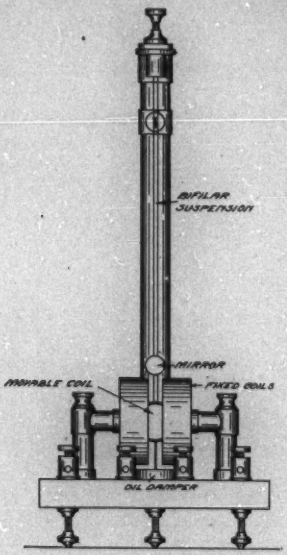
BIFILAR SUSPENSION
MIRROR
MOVABLE COIL
FIXED COILS
OIL DAMPER

FIG. 1

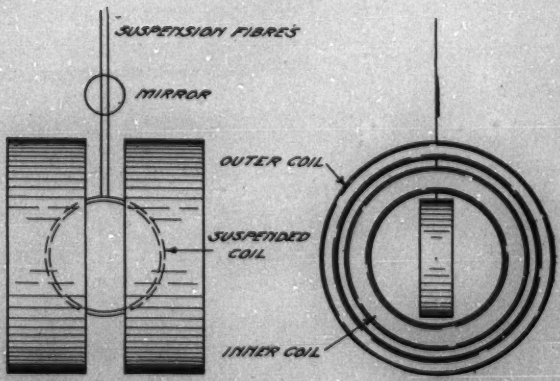
SUSPENSION FIBRES
MIRROR
OUTER COIL
SUSPENDED COIL
INNER COIL

FIG. 2

equals to within a constant the instantaneous value of the variable current for the particular setting of the contact maker used. The constant of the instrument is readily obtained by measuring the ratio of the currents in the two fixed coils required to produce no deflection of the movable coil when a small current from a separate source is sent through it.

Shifting the contact maker arm, as many points may be obtained as are desired. The instrument is extremely sensitive, allowing perfectly satisfactory traces of currents a fraction of a milliampere effective value to be obtained, and its range may varied to almost any extent by the addition of fixed coils. When measuring very small currents, it must, however, be shielded or corrected for stray fields.

Briefly, the advantages of the instrument are as follows:

(*a*) Its indications are independent of the constancy of contact, being a zero method.

(*b*) All readings are of instruments of the Weston direct current type, and may be readily converted to absolute values.

(*c*) Wide range and great accuracy.

(*d*) It may be quickly and easily manipulated and has a minimum resistance and inductance.

Some of the applications to which it has been put are:

(*a*) The tracing of A. C., e.m.f. and current waves.

(*b*) Obtaining curves of growth and decay of current in inductive circuits, when constant e.m.f.'s are applied.

(*c*) Obtaining curves of rate of growth and decay of such currents.

(*d*) Obtaining leakage coefficients of large generators, the time constants of whose fields make the use of ballistic or of damped galvanometers for accurate work impracticable.

(*e*) The determination of the variation in a single revolution of the angular velocity of engine fly wheels.

(*f*) The determination of the fluctuations in currents from commutating machines.

In Fig. 3 are seen the connections for obtaining an ordinary current wave from an A. C. generator. A milliammeter is put in series with the movable coil of the instrument as a convenient means of knowing whether or not the contact maker is operating satisfactorily. The average current through this ammeter need not exceed four or five milliamperes; this is so small as not to injure the contact points and allows the period of contact to be extremely small.

For obtaining e.m.f. waves of an A. C. generator, a larger number of turns of fine wire are used in the outer fixed coils, together with a suitable non-inductive resistance in series with them, the whole being connected across the generator terminals.

In Fig. 4 are given the e.m.f. and exciting current waves for a small 1½ k.w. transformer of well-known make. It will be noticed that the smallest variations in both curves are faithfully reproduced. It should also be remarked that such curves check exactly with curves obtained by other reliable methods.

Fig. 5 gives the connections for obtaining the curve of rate of growth of current in an inductive circuit when a constant e.m.f. is applied. A pendulum contact-making device is shown, as it happened to be available, but other means may, of course, be substituted. The inductive circuit as seen, consists of the fields of an Edison bipolar dynamo. About the fields is wrapped a

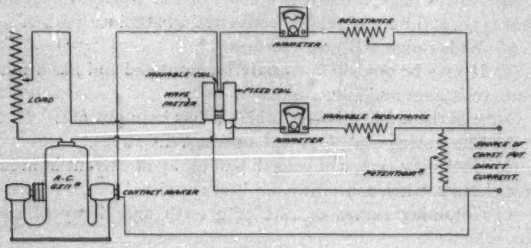

FIG. 3.

test coil of fine wire. At determined times after the making of the field circuit, the instantaneous values of the current induced in the test coil are measured, and together form a curve of rate of growth of current in main coils. The area of this curve is proportioned to the total induction passing through it. Now, if a second coil, having the same number of turns and of equal resistance, is wound about the armature and the area of the induced current curve in it similarly obtained, the ratio of the first to the second area is the leakage coefficient of the dynamo. Fig. 6 gives the results for a certain field excitation. While not adapted to shop measurements, this method is an absolute one and serves to check the method now commonly used, namely—taking the ratio of the kicks of two similar Weston voltmeters or ammeters,

one in a test circuit about the fields and one in a test circuit about the armature.

Fig. 7 shows the curve of growth of current with time in the

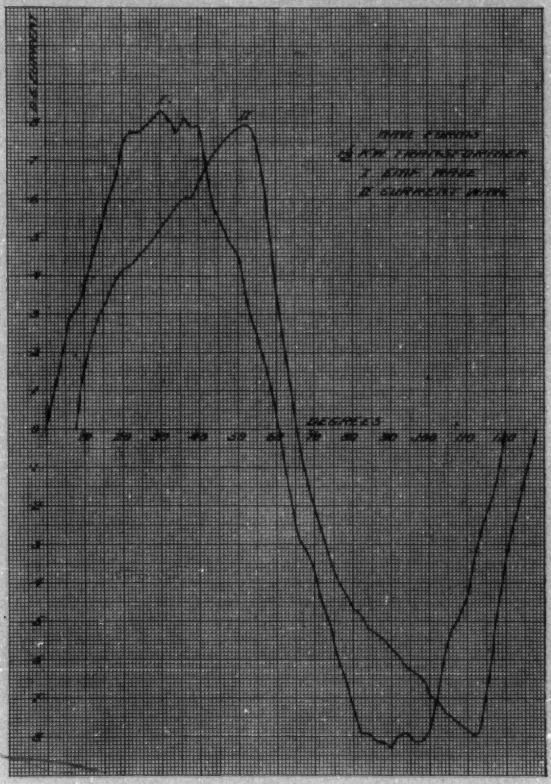

FIG. 4.

fields when a constant e.m.f. of 110 volts is applied. The connections of the instrument for this curve are not given, but are very simple, as a little consideration will show.

The variation in a single revolution of the angular velocity of an engine fly wheel is measured as follows: A disc dynamo with fields constantly excited is directly driven from the engine

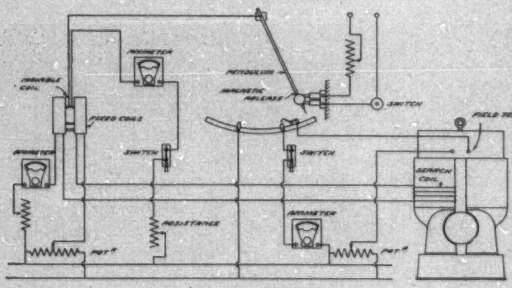

FIG. 5

shaft and the current trace from it obtained as a function of angular displacement, such current at any instant being proportioned to the angular velocity of the fly wheel at the same

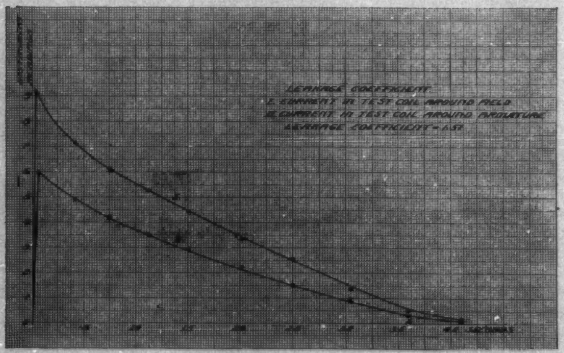

FIG. 6

time. It is necessary to use a disc dynamo, or one having a great number of commutator segments, as otherwise the variations in the current due to the angular displacement of adjacent arma-

ture coils will mask the variations due to a change in angular velocity.

Most accurate results are obtained by adding to the instrument a third fixed coil, through which is sent a direct current, just sufficient to neutralize the dynamo current corresponding to the minimum angular velocity of shaft or dynamo. The D. C. current in the second fixed coil will then correspond directly to the variation of angular velocity from its minimum.

In the first experiments made, a dynamo with a twenty-four-part commutator was used, but the curve obtained showed twenty-four variations in one revolution, each of which greatly

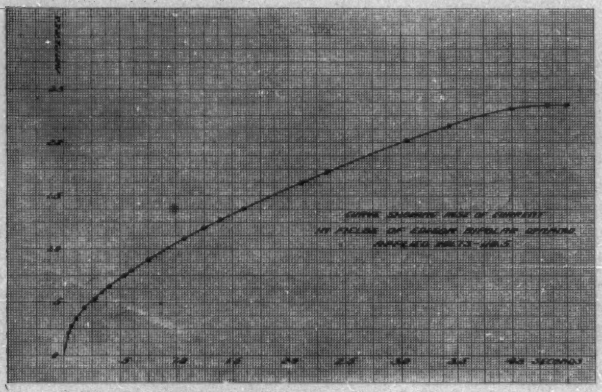

FIG. 7

exceeded in amount the variation of their mean maximum from their mean minimum.

Driving the armature of this machine at a uniform speed by means of a motor taking current from a storage battery, twenty-four similar variations per revolution were observed in the current curve, which measured, of course, the fluctuations corresponding to the pitch of the armature coils in this particular machine.

Uses for the above instrument other than those cited will readily occur, but perhaps enough has been said to indicate that it has a considerable value for general laboratory purposes.

My thanks are due to Messrs. Smith, Dunfield and Murphy, graduates of the class of 1902, for much assistance in its development and for the taking of observations.

Delivered at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington Mass., June 21st, 1902

PRESIDENTIAL ADDRESS.

BY CHARLES P. STEINMETZ.

GENTLEMEN:—With to-day's meeting ends the first INSTITUTE year in the new century, and it may be appropriate then to look back into the work achieved and forward into the future.

At the entrance of the 19th century we see empirical science struggling for recognition against metaphysical speculation. At the entrance of the 20th century metaphysics has practically ceased to be considered, and empirical science is universally acknowledged as the source of all human progress. In gradual advance from success to success this victory has been won. Empirical science can now expand without any restraint. But with the removal of the opposition of a hostile philosophy, has been removed also the searching criticism into the correctness of the results, the methods and the theories propounded by empirical science, and thereby the absolute safety which characterized the work of the earlier period. Herein lies the greatest danger to the unbroken progress of science.

Facts, whether observed incidentally or intentionally by experiment, are the foundation of science. But the mass of facts has accumulated so as to be beyond comprehension, and we are forced to work with the conclusions from the facts, the empirical rule, theory and hypothesis, and have become so used thereto that gradually the dividing line between the theory and the underlying facts has become blurred, so that we attribute to the theory the same certainty as the facts on which it is based. But, however well a theory represents the fact and proves its value in successful application, it unavoidably

contains besides the facts on which it is founded, foreign elements, mainly the personal equation of its originator and the personal equation of its times. When building upon theories, the danger exists that instead of building upon the facts represented by the theory, we may build upon the personal equation of the time, without realizing the unsafe foundation of our structure.

The reverence for facts as the foundation of science has been extended to the theories based upon them. But when by building theories upon theories, conclusions are derived which cease to be intelligible, it appears time to search into the foundations of the structure, and to investigate how far the facts really warrant the conclusions. If we are told of matter moving in a vacuum tube with velocity comparable with that of light, of small chips breaking off atoms, of free atoms of chlorine and sodium floating around in a salt solution charged with opposite electric charges, whatever that may be, of electricity being propogated not through the conductor, as we used to assume, but through the space surrounding it, etc., it is time to pause and try to understand.

In the gradual replacement of facts by the belief in theories more or less inadequately representing the facts, lies the chief danger to further scientific progress. Here is a field where splendid work in destructive criticism can and should be done by the younger generation, which, after leaving college with all the theoretical armament required, is not yet handicapped by personal relations with the men whose names are identified with the ruling theories.

Especially for our branch of electrical engineering, this is of fundamental importance, since all the success of our work depends upon the absolute safety of the foundations on which we build.

All future progress in science and engineering depends upon the young generation, and to insure an unbroken advance it is of pre-eminent importance that the coming generation enters the field properly fitted for the work.

Here the outlook appears to me by no means entirely encouraging.

It is not the object of the college or university to turn out full-fledged engineers who can handle any engineering problem of any magnitude. The available time is altogether too short for this, and a very great deal of practical experience is

required which is not available to the educational institution. It is not necessary, either, and the college graduate is not expected to take immediate charge of engineering works of great magnitude. All the educational institution can do and should do is to fit the student to take up the practical work as efficiently as possible, and to give him *a thorough understanding of the fundamental principles of electrical engineering and allied sciences*, and *a good knowledge of the methods* of dealing with engineering problems.

At present the average college course does not do this.

One of the reasons of the inefficiency of the present college course is the competition between colleges. By trying to teach more than other colleges, the quantity of material taught has gradually increased so that it is no longer possible to give a thorough understanding, and memorizing takes the place of understanding. Memorizing, however, is an entirely useless waste of energy, since anything that is not perfectly understood, but merely memorized, will be forgotten in a short time if not continuously applied, and if continuously applied it would be remembered anyway. If of the amount of material in electrical engineering as well as other branches which the educational institution of to-day attempts to teach, one-half or more should be dropped altogether, and the rest taught so as to be fully understood, with special reference to general principles and methods, the product of the institution would be far superior and more successful in practical life. To be dropped, then, are all formulæ, rules, etc., beyond the most simple ones, of the scope of the multiplication table, etc. When needed, formulæ can be derived from the fundamental principles or looked up in the literature, and their memorizing is a mere waste of valuable time, useless since the memory cannot retain what the understanding is unable to reproduce from its premises. This, for instance, applies to the various formulas of electromagnetic induction, the equations of the transformer and other apparatus, and to theoretical investigations in general.

Still more than to electrical engineering this applies to the allied branches of science and engineering, of which the electrical engineer should have a fair understanding. Here anything beyond fundamental principles is objectionable. The electrical engineer should understand the principle of the steam engine, of the hydraulic turbine, should know why the spouting velocity and the peripheral speed of the water-wheel are related to each other

theoretically, and how this relation is modified actually, but he should not memorize the mathematical theory of the turbine with its half dozen unknown friction coefficients. He is not expected to design turbines, and if he did his design would surely be a failure, but he is expected to understand the turbine, the steam engine, etc. The engineering graduate should know the principles of the strength of materials, the distribution of forces in the loaded beam, the reasons leading to the I beam, and to the triangle in bridge and roof construction, but time should not be wasted in calculating bridges or deducing elastic curves, etc.

In short, in electrical engineering, and still more in all allied branches, nothing beyond the general principles is needed for success, but the principles should be fully understood, and with the limited time at the disposition of the student this cannot be done if time is wasted in memorizing things to be forgotten afterwards.

One objectionable feature of the instruction of most colleges is the step by step method. One subject is taken up, by application of sufficient time and energy pushed through, and then after passing an examination dropped to take up another subject. It is true that by steady application to one subject a great deal can be learned and splendid results derived in the examination papers, but all that is learned in this manner is just as rapidly forgotten. To understand a matter thoroughly, so as really to have a lasting benefit from it, and not merely make a good showing in examination papers, requires several years familiarity. Therefore, any subject, that is not kept up during the whole college course might just as well be dropped altogether and the time spent therein saved.

We hear that college graduates have no mastery of language, cannot express themselves logically, and it is therefore recommended that more time be devoted to literature and instruction in the English language. But as long as we do not teach logic, but have the English language taught by philologists, more or less of the character of the florid newspaper style, that is to write very many words on a very small subject, no useful results can be expected. Logic should be taught by a scientist, and the principle of English teaching to engineers should be to enable them to explain a subject intelligently and logically, with as few words as possible. That is, Faraday's researches, and not the product of the successful novel writer should be the example aimed at.

The combination of text book and home work offers a splendid means by which incompetent instructors may make an elegant showing in examination papers, and turn out a very inferior grade of men, men who sometimes do not even know what real understanding means. Free lectures on subjects which the instructor himself thoroughly understands (which is by no means always the case now) make it possible to direct the course so that the student's understanding follows it, and in this case home work becomes superfluous, except in connection with the laboratory. Reviewing the lectures and filling out the gaps due to absence, etc., appears to me the only legitimate requirement on the student's time outside the lecture room.

The present method of examination, which consists in expecting the student to answer ten questions or so within a few hours, is faulty. It shows what the student has memorized, but not how far he understands it. Furthermore, the brilliant student who usually answers nine questions out of ten correctly and would have answered the last if he had not made a slight mistake, displaced a decimal point or so, in practical life may be utterly useless, since while doing very rapid work, his work is not reliable, while a slow man who, however, can absolutely rely on the correctness of his work, will be very successful in practice while hardly passing the college examination.

What, then, should an ideal electrical engineering course contain?

Of mathematics, plain and some solid geometry, arithmetic, and a good knowledge of algebra. Plain trigonometry—no spherical trigonometry required—and a thorough understanding of analytical geometry and of calculus, but no memorizing of integral formulæ, etc.; they can always be looked up in a book when needed.

A thorough knowledge of general physics, especially of the law of conservation of energy, which I am sorry to say is not yet an integral part of our thinking, and of chemistry, especially theoretical chemistry and chemical laboratory, in the latter freely using tables, etc.

The electrical laboratory work should be taken up right at the beginning. Even before taking up the theory of apparatus, the theoretical investigation of alternating currents, self-induction, transformers, etc., the student should have met these phenomena and handled the apparatus in the laboratory. Only after seeing the effects of self-induction, for instance, on the alternating

current circuit in the laboratory, will the theory of self-induction have any meaning or make an impression on the student. What the student has seen practically in the laboratory he will then take up in the theoretical course, and understand it, he will learn to calculate and control, and afterwards, going back once more to the laboratory, to apply it. It is here that the average college graduate is inferior to the practical man, and in spite of his handicap regarding theoretical knowledge, the latter frequently pushes ahead of the college graduate because of his superior understanding of the phenomena, based on his familiarity with them.

Design of electrical apparatus is of very secondary utility and rather objectionable, with the exception perhaps of some very simple apparatus. The considerations on which designs are based in the engineering departments of the manufacturing companies, and especially the very great extent to which judgment enters into the work of the designing engineer, makes the successful teaching of designing impossible to the college. Far better is the reverse operation, the analytical investigation of existing apparatus, and more instructive to the student. That is, to derive from existing first class apparatus by measurement and test, the constants of the apparatus, and to calculate these constants and compare them with tests. Besides, a very small percentage of the college graduates enter the field of designing, but most of them will have to handle apparatus, and it is therefore very much more important to be familiar with the completed apparatus in all its characteristic features, in normal and in abnormal operation, than to be able to design it.

The preceding naturally can be a short outline only of the work which I consider appropriate to an electrical engineering course, but I believe the general principles of the course can be understood from it. They are, to give the student all the ground work required to be successful in future practice, but not the impossible aim of giving him a complete education as a practical engineer.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 21st, 1902.

CONCERNING UNIFORMITY IN THE ELECTRICAL ENGINEERING COURSES IN THE UNITED STATES.

BY SAMUEL SHELDON.

Technical schools and other higher educational institutions, considered as business corporations, are of necessity conducted in a unique manner. Like ordinary business concerns they are sellers of goods, namely, knowledge and educational wares, the students being the customers and paying in money, in time, or in both. The educational institution is in the peculiar position of being able to dictate the things which the customers must purchase, and the customers, furthermore, are not in a position to determine the quality and genuineness of the goods delivered. The condition is modified somewhat by extensive use of the elective system. Because of this condition of affairs, it is of great importance that the professors, the directors, or those who are responsible for the curricula should be well-informed and broad-minded men, be possessed of good judgment, and be free from personal motives or bias. The selection of the curricula of the technical courses in our country has unquestionably been influenced by competition in the form of friendly rivalry and by the information given in the papers, the discussions and the personal intercourse of the various professional societies, especially of the Society for the Promotion of Engineering Education.

The determination of a curriculum does not, however, lie wholly in the hands of the officers of the educational institutions. The history of our technical schools from the foundation of the first one at Troy in 1824 to the present, with its problem of ever-increasing numbers in the laboratory, shows an influence on the part of the student body. This body has distinctly utilitarian purposes. The average student attends a technical school in

order to get that which will enable him to earn a living. He desires a better quality of living than he could hope to get otherwise, and he wishes to get it as soon as possible. Such haste may not be for his good, but the mental attitude exists and its existence must be recognized. Probably every instructor has conversed with undergraduates who wished to discontinue their studies and take up, to their minds, lucrative positions, which had suddenly become available. A lack of recognition on the part of classical colleges of this impatience of the average student, may account for their apparent conservatism in the past toward technical instruction. At any rate, to its recognition is due, to no small extent, the rapid growth of the technical institutions.

A course in electrical engineering, to meet the desires of its patrons, should be laid out with a view to securing the best possible positions for its graduates. The student body is made up of some brilliant students, some dull ones, and many of medium ability. The course should be adapted to the wants of the last class. The brilliant man will lead his fellow students and will always look out for himself. The dull student will lag behind, but will be much benefited by the struggle.

The average electrical graduate takes a subordinate position with people engaged in the construction, the sale, the erection, or the operation of electrical machinery. The initial rapidity of his advancement depends upon his technical education and could be made a maximum by a thorough understanding between the employer and the educator. His ultimate position seems to be dependent almost entirely upon himself and very little directly upon any special feature in his educational training. Inquiry of employers reveals the fact that there is considerable dissatisfaction with graduates, irrespective of whence they come; that employers prefer to do their own special training and to supply the graduate with his special facts; and that employers consider that the average graduate lacks something, and this something is variously and often vaguely defined as: "initiative of thought and action," "breadth of training," "breadth of thought," "training in fundamental principles," "horse-sense," etc.

By reference to the catalogues of a large number of institutions and to Caldwell's admirable comparative table of electrical engineering courses[1] the following table has been made, which shows the maximum, the minimum and the average time devoted to various subjects in various institutions. The time unit is one

1. Proc. Soc. Prom. Eng. Education, VII, p. 128.

hour per week per academic year. This equals about 36 actual hours of lecture, of recitation, or of quiz, or 72 actual hours in the drawing-room, the laboratory or the shop.

TIME DEVOTED TO SUBJECTS.

Subject	Time in any one institution.		Average time in all institutions.
	Minimum.	Maximum.	
Mathematics	5	11	9.2
Drawing	3	10	6.2
Physics and Chemistry	7	25	14.0
English	0	11.3	4.5
French and German	0	10	4.9
Shop-work	0	21	7.5
Electrical Engineering	9.5	23.8	16.5
Other Engineering	7.7	23.2	15.8
Thesis and Elective	0	7.1	0.3

There is considerable uniformity of requirements in mathematics, in physics and in chemistry. Apparent differences of time in the above table are compensated by differences of entrance requirements. The time spent on other subjects varies greatly in different institutions. As an instance, electrical engineering students at Cornell spend ten times as much time on shop-work as those in the Massachusetts Institute of Technology. Such differences in the curricula of institutions of unquestionably high standing suggest prodigality in the expenditure of a student's time and suggest the possibility of obtaining much higher teaching efficiency by the adoption of uniform curricula, uniform not only as to the time to be devoted to the different subjects, but also as to the topics to be treated in that time and as to the manner of their treatment. The instruction given in preparatory schools has been very much improved by the standardization of their courses. The time thus saved could be devoted to subjects which would tend to produce the results which employers of graduates now consider as wanting. Perhaps that which the present graduate lacks is the broad-mindedness associated with graduates from classical and art courses and which, as a whole, is considered as an indication of a liberal education.

The results which the liberal educator aims to achieve in his student are the following:

(1) To discipline his mind so as to create a power for coördinate thought.

(2) To impart to him a knowledge of facts.

(3) To develop a power of expression in language or in action.

(4) To discipline his emotional sympathy so as to develop an æsthetic taste.

(5) To discipline his moral faculty.

The first three are also the aims of a technical education and are accomplished through the study and treatment of special facts lying in a very narrow field. The facts employed by the liberal educator are drawn from the whole domain of human knowledge and are purposely chosen so as to give the student a superficial and general survey of human achievement. A knowledge is imparted of man's relations with the material universe by facts drawn from the natural sciences; with his thinking self or soul by a study of psychology, of logic and of mathematics; with his fellow man of the present from a study of ethics, of economics, of politics and of sociology; with his fellow man of the past, from a study of history; with the universe as a whole, from a study of philosophy; and with God, from a study of religious ideals and problems.

This curriculum has a two-fold purpose; first, to assist the student in choosing a calling which will be congenial and suited to his abilities, and secondly to develop roundly all his faculties, so that he may properly use his senses for pleasure, his intellect for truth, his emotions and æsthetic nature for beauty, and his will for right and duty.

The average graduate from a liberal course possesses a breadth of culture which is easily distinguished as being in excess of that possessed by the average technical graduate. The two courses have so many immediate purposes in common that this difference might be largely eradicated by a single carefully planned course of lectures.

It is objected that a uniformity of curriculum leaves no opportunity for the exercise of the individuality of the professor. A man who is strong in one branch, it is urged, should devote more time to that branch than to others. It seems as though the place for individuality were in the university, and, if exercised in the technical institutions or departments, it should be combined with special advantages of material equipment in the same branch or with special conditions due to the location of the institution and its environment. The legitimate ultimate purposes of a technical institution are so utilitarian and different from those of the liberal institutions that the extensive use of electives *on the part of professors*, which is so admirably adapted to ordinary college requirements, is detrimental to the best interests of the technical student and is wasteful of his time.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 21st, 1902.

ELECTRICAL ENGINEERING COURSES AT COLLEGE AND THE EDUCATION OF THE ELECTRICAL ENGINEER.

BY WILLIAM ESTY.

I wish to preface my remarks on electrical engineering education by thanking President Steinmetz for his thoughtfulness and broad-minded policy in giving to the teachers of electrical engineering this opportunity for discussing with those eminent in the profession their ideas on how electrical engineering should be taught. By providing this clearing-house for the exchange of ideas, the intimate relations between the engineer, the manufacturer and the college will be revealed, and a better understanding of the requirements to be met by our technical graduates in commercial work, will result. In these ways and others, the cause of education will be greatly benefited.

The New Situation.

In the pioneer days of the older branches of engineering, there was required, except for elementary mathematics, but little scientific knowledge. In this stage, engineering was an art, not a science, and hence as in all the arts, the regular method of instruction was by apprenticeship. The pioneer engineers were all men of little education, but of considerable training in the school of experience.

This old régime has passed away, and a new situation has arisen with the growth of modern science. We have a rich inheritance of accumulated wisdom and experience, but he who would possess it must earn it by strenuous toil. For no one who has not mastered the sciences which his predecessors have devel-

oped can hope to attain success in engineering to-day. The common school education, enough for the pioneer, is no longer adequate. Experience has shown that the most direct road to the mastery of the sciences lies through the college. Other things being equal, a student can gain a better and broader education in less time by attending a first-class college than in any other way. I think we are all agreed on this point, and it is the recognition by the public of this fact that accounts for the marvellous increase in the number of students enrolled in our technical colleges. This number has more than trebled in the past decade, and is now over 10,000. There are more than fifty institutions in this country giving instruction in electrical engineering, and the students pursuing this course alone number over 2,500.

The Recognition of the New Situation by our Professional Schools.

In all professional schools there is a growing tendency to increase the requirements for admission and to raise the standards of graduation. Thus a few of our older and larger institutions have come within a few years to require in the applicants for admission to their law and medical schools, at least four years of college education.

As engineering has rightfully come in recent years to rank as one of the learned professions, it is worth while to ask why the long and severe preparation now so freely conceded to be necessary for the proper equipment of the lawyer and doctor, should not be deemed equally necessary for the engineer. There is hardly a thoughtful engineer who is willing to admit that his profession makes any less demand upon his powers or requires any less skill, perseverance or energy than the profession of law or medicine makes upon its followers. Why, then, should the preparation of the engineer for his life work be any shorter or less strenuous than that for law or medicine?

The Importance of the Study in College of History, Economics and Literature.

Besides the thorough grounding in the principles of the sciences of physics, mechanics, chemistry and mathematics, the well-trained engineer needs a broad elementary training in other departments of human knowledge. He should know something of history and economics, of language and literature, that he

may correctly estimate the limitations and relative value of his own work and thought in comparison with the work and thought of other men. It is especially through the so-called culture studies and the broad outlines of general knowledge, serving to put a man in touch with all times and all men, that a broad outlook and wide sympathy can be acquired.

The Coming Education for the Engineer.

The ideal education for an engineer, and I use the word ideal meaning something that is to be, is a literary and scientific course of a general nature covering three or four years, followed by a special technical course extending over two or three additional years. Recognizing the undoubted advantages to the student and to the profession of both general and technical education, some of our colleges are encouraging this practice by making it possible for an earnest student to complete both courses in six years. Similarly, graduates of reputable literary and scientific institutions may secure a degree in engineering at some of our best technical schools within two years; and the tendency to regard an engineering course as post-graduate professional work is increasing, as is evidenced by the increasing number of graduates of literary colleges taking engineering studies.

The Compromise.

Granting, then, that a preliminary liberal college education is a good, if not a necessary, preparation for the electrical engineer to-day, it is of the utmost immediate importance to determine how we ought to organize our technical courses to produce the best results possible in the limited time of four years. The proper choice and sequence of the studies is a matter of great difficulty, for under present conditions we must satisfy the demand for both a fair general education and a technical training, all to be compressed within the short four years.

An examination of the catalogues of colleges giving four-year courses in electrical engineering will show the following divisions of time allotted to the different groups of studies in the electrical engineering course.

Culture studies (English, modern languages, etc.) . 10%–20%
Indirect technical studies (mathematics, physics, drawing, shop, etc.) 30%–40%
Technical studies 50%–60%

The electrical engineering course at Lehigh University em-

phasizes the importance of culture studies to the extent of making them 18% of the total, giving 32% of the time to indirect technical studies, and 50% to professional subjects.

It is the common experience that it is impossible to teach culture subjects effectively in a course with decided technical tendencies. The student underestimates the value of the culture studies, and hence devotes most of his energies to the technical subjects. The disadvantage of this situation is two-fold. The student is apt to conceive a dislike for subjects studied in a half-hearted way, and he fails to secure a return commensurate with the time and effort devoted to these studies. This difficulty is a significant warning that our present practice of combining two radically different groups of studies in a single four-year course is fundamentally wrong.

Status of Electrical Engineering Courses Compared with Other Branches of Engineering.

With our older engineering courses, such as civil and mechanical engineering, educational materials and methods have become pretty well established and fairly uniform the country over. Long experience has demonstrated in general what studies are best to include in the curriculum, what the sequence of subjects should be, and there are excellent standard text-books to be had. In electrical engineering the case is quite different. To begin with, the profession of electrical engineering is a very recent one. Invention and industrial applications of electricity are growing with bewildering rapidity. Practice is changing radically day by day. Subjects like the long-distance transmission of power and most of the electro-chemical developments are scarcely ten years old. As a result of these unprecedented conditions, it is but natural that teachers of electrical engineering should be feeling their way, experimenting to find a solid foundation on which to build a substantial course for electrical engineers.

The question of text-books, especially those dealing with the practice of electrical engineering, is a serious one. A book can hardly emerge from the press before it is out of date. It seems, moreover, to be a common impression, at least as far as books on the practice of electrical engineering are concerned, that those who know most about the subject will not tell what they know, while those who do not know, frequently write the books. Hence, for the latest developments and current practice, teachers of electrical engineering have to depend mainly on the transactions of the engineering societies and other periodical literature.

Again, as to the amount and kind of published technical information, a radical difference is to be noted. In the journals of mechanical and civil engineering, appears full and detailed information on the latest designs of locomotives, machine tools, steam engines and boilers, bridges and other engineering works. In electrical engineering, on the contrary, very little detailed information about recent machines and apparatus is ever published. This state of affairs seems to be peculiar to America, for in Germany and other foreign countries the unwillingness to publish data and results of tests is not characteristic of manufacturers. I confess I am unable to account for this radical difference in custom prevailing between the electrical and other branches of engineering. Whatever the explanation of the difference, it is certain that in this regard the teacher of electrical engineering is severely handicapped in comparison with his colleagues in civil and mechanical engineering.

Commercial Aspect of Electrical Engineering.

A common complaint among practicing electrical engineers is that college graduates are not practical. This criticism is well founded, but it is a necessary and logical consequence of our scheme of education. When an employer engages the services of a man just graduated, he should not expect him to be exactly fitted by a college education for the practical work he is hired to do. What the employer should expect is a thorough grounding in principles, so that the young man will be able easily and quickly to master the details of his particular work and carry it on with success. The kind of technical education herein advocated aims not to make the graduate immediately successful in commercial life, but aims rather at ultimate success.

While we all admit that commercial conditions are always present in engineering, we would probably likewise admit the difficulty, if not the undesirability, of attempting to give formal instruction in purely commercial affairs. At the same time, teachers recognize, I think, that manufacturers and engineers are on the watch for technically trained men with business instincts. We likewise realize that the most successful technical graduates are those in close touch with commercial life. How, then, may we help to keep our engineering students in touch with current practice and affairs? Various ways are possible, each of which has its peculiar advantages.

(1) By familiarizing the student with the so-called trade

literature, including manufacturers' and dealers' catalogues. In this literature may be found examples of the latest and best designs, and often technical information of great educational value. To make these catalogues of the greatest benefit, there should be facilities for filing and preserving this useful material for ready reference.

(2) By securing from manufacturers drawings, photographs and samples of their product. Lantern slides made from photographs of the latest apparatus and electric plants, are an important aid to the teacher in keeping his students in touch with current practice.

(3) By visits of inspection to manufacturing establishments and electric lighting and power plants.

(4) By encouraging the student to engage in practical work during his summer vacations.

(5) By securing periodic lectures from men of affairs, or from specialists in certain lines. To see something of the personality of a man eminent in his profession, to be brought from the class room into an atmosphere of affairs and engineering realities, is to the student an inspiration. Would that more of our practicing engineers might realize the possibilities in doing this missionary work for our colleges.

Laboratory Work.

One of the most important advances in engineering education has been the introduction of the laboratory method of instruction. Many of our technical schools have a large and expensive equipment of apparatus the chief object of which is to aid the work of instruction. In the emphasis put on laboratory instruction, our American schools lead the world. But even with the equipment it is not easy to organize and plan a laboratory course that will always yield the best educational results. In some colleges, too many experiments are undertaken. With such, quantity rather than quality of work appears to count. In some cases, owing partly to the large number of students in proportion to instructors, and partly to save time, the galvanometers, bridges or dynamos are all connected and wired up in advance by the instructor. The exercise consists in having the students take certain readings and observations which they record in notebooks. These readings are then taken home and "worked up," and the results handed in. This mechanical procedure pretends to be laboratory work.

As an illustration of the other extreme, sometimes used in conducting laboratory work, take the actual case that came to my attention not long ago. It was the practice of a certain professor to assign in the laboratory a particular dynamo to a pair of students with the laconic remark, " go and find out all about that dynamo." The students thus turned loose in the laboratory tried to carry out their instructions, and with but little help, advice or direction, used to potter over that one dynamo for months at a time. Now of these two extremes in laboratory management, the latter is certainly the better. For what those students finally knew about that dynamo was considerable, and best of all, it was first-hand knowledge, the only true knowledge. The method, however, was at fault in this case in being overdone, since from lack of directed effort, the students wasted much valuable time.

Too great care cannot be taken lest laboratory work be over-directed or under-directed. The only satisfactory way is to divide a class into small sections, and devote much time, especially at the beginning of the work, to individual instruction. Handled aright, the student can be taught to think and act for himself. But without constant watchfulness and judicious direction, all the immense power for education possessed by the laboratory method may be entirely lost.

Perhaps the chief value of laboratory work is to give the student that critical, painstaking, conservative attitude of mind known as the scientific spirit. A student who from two or three hasty measurements is confident that he has discovered a new principle, has failed to acquire the scientific spirit. Faraday spent seven years of patient toil in the laboratory before he was able to announce the law of electro-magnetic induction, which seems simple enough to us.

Design as a Class-Room Subject.

There are doubtless many present who think that the teaching of electrical design should not be included in a college course for electrical engineers. I am very strongly of the opinion that such a course, if presented and developed in the proper way, may be made of great educational value. This conclusion is based on nine years of experience in teaching the subject to students, and is confirmed by the experience of graduates of several years' standing who have taken the work.

A course in electrical design gives occasion for the application of the abstract principles of electrical science to problems which

approach laboratory exercises in their character of reality. Such applications give to theoretical study an effectiveness not to be reached in any other way.

According to my practice electrical designing is begun at the commencement of senior year, and the time usually devoted to it is from four to six hours per week throughout the year. The course includes a study of the materials of electrical engineering, and a detailed study and calculation of electro-magnetic mechanisms, dynamo-electric machinery, and transformers. Work at the drawing board is reduced to a minimum.

Dynamo designing is both an art and a science, according to the point of view. As an art, designing depends mainly upon experience, skill, and judgment, modified by commercial limitations. Design, as an art, cannot from the nature of the case, I think, be properly taught in college. Designing as a science is based on the fundamental laws of electricity, magnetism and mechanics. This phase of designing can be taught to students, and is an important supplement to the study of dynamo-electric machinery.

The Seminary Method of Instruction.

The seminar may be regarded as a form of laboratory work in which the library is the work-room, and the books and periodicals on electrical engineering are the pieces of apparatus. For many years I have used the seminary method with the object primarily of cultivating in the student the habit of reading systematically the current electrical periodicals. Special topics are assigned to the students for investigation, and their reports made in writing are read and discussed before the class. The latest developments in electrical industries are discussed and matters pertaining to thesis work are presented by the students, either in writing or orally before the class.

The special advantages possessed by the seminary method are as follows: It gives familiarity, in the proper way, with the resources of electrical engineering literature; it requires discriminating and substantial work of a kind not demanded by other educational methods; it furnishes valuable information to the student on topics which for lack of time cannot be fully developed in the recitation and lecture; it stimulates the student's interest and is a relief from the monotony of the formal recitation; as an exercise in English, it may be more valuable than the regularly prescribed essay or theme, for being merely

a means to an end, self-consciousness is lost, and individuality in style is permitted freer play. The seminary method is most successful when used with advanced classes of limited size.

A natural outgrowth of the employment of the seminary method in the discovery by the student of the need of a system by which information on a given technical subject may be easily found. Here, then, is the opportunity for the teacher to introduce the student to the various published indexes to engineering periodical literature. But printed indexes are only of limited use, as most of them do not pretend to keep up to date. For keeping track of current electrical literature the only satisfactory method I have found is the card index system. When in reading a journal, I find an article which I will probably need again, I make a reference to it on a card with a brief abstract of its contents, and file it away under an appropriate heading in a card cabinet. In connection with the electrical engineering seminary at Lehigh, a part of the work consists in giving the student practice in indexing and making abstracts of the more important articles in the electrical journals. The habit of quickly scanning the columns of technical papers in order to seize the salient points in an article for record upon a card, is worth cultivating in students. For next to knowledge, the best thing is to know where to find it. Accordingly, my senior students are started on making card indexes for themselves, and the habit formed in college is generally continued with increasing advantage in their professional life.

Thesis Work.

In most of our technical colleges the candidate for graduation in electrical engineering is required to devote a part of his senior year to writing a thesis. The function of the thesis, it seems to me, is to bring to a focus on some definite object all the accumulated knowledge and experience of the student. To be most valuable, the thesis should be largely experimental in character. Some definite topic or investigation is first chosen with the approval of the instructor. The student then consults the published work of others along similar lines to find what has and what has not been done. Next the plan of campaign is settled and the instruments are standardized. After the experiments are made, the results are corrected, tabulated, plotted and discussed. Finally, conclusions are drawn from the results.

From the standpoint of training, it matters little whether the

work done or the conclusions drawn, are old. The main point is that the work be independently performed by the student and thus far original with him. He should be thrown on his own resources and be expected to accomplish independently definite results. It falls to the lot of very few undergraduates to succeed in making a discovery, or even to make any real contribution to knowledge. Nevertheless, thesis work gives peculiar opportunity for the exercise of the critical faculty, for the following of scientific methods and above all, for the patient overcoming of experimental difficulties. And as a trial of strength and a measure of character thesis work is unsurpassed among the activities of the technical student.

In conclusion, I wish to express in the strongest terms my conviction that safe rules to follow in laying out a course for electrical engineers are: to teach thoroughly those things in college which are fundamental; to devote little time to highly specialized subjects; to introduce the student to those branches of knowledge which in his later life he can acquire only with increasing difficulty, if at all; and to endeavor to cultivate in him the hunger and thirst for more and deeper knowledge, so that he will remain a student through life.

Lehigh University,
South Bethlehem, Pa.,
June, 1902.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 21st, 1902.

THE EDUCATION OF THE ELECTRICAL ENGINEER.

BY HAROLD W. BUCK.

Electrical engineering is probably the youngest of all the professions, for it has hardly been recognized as a regular profession for more than fifteen years past. As a result, the men who have reached prominence in it to-day have attained their positions from widely differing courses of preliminary training; many of them are men who started life in other lines of work and afterward turned to electrical pursuits on account of the sudden growth and importance of the business. In consequence of this, all methods of preliminary education are represented and their relative values may be estimated.

The argument runs largely between two classes of men, one represented by the so-called " practical man " and the other by the theoretical electrician; the graduate of the machine shop and the graduate of the university. Both of these types have attained success, but the correct answer to the argument will probably be found in a proper combination of the two types. In the past some of the most successful electrical engineers have belonged distinctly to the class of practical men with little theoretical training, but the conditions have changed. In the early days of the profession there was little theory or predetermination of results, and work was carried on largely by guesswork, or by cut and try approximations. At the present time, however, such a state of development has been reached that exactness of result is essential to success, and work based upon exact theory becomes imperative.

In a stationary condition of an art a man with practical experience only may become very familiar with all the existing types

of apparatus and, knowing their various applications, may qualify, to an extent, as an engineer. But the extraordinarily rapid growth of the electrical arts places electrical engineering apart from all the other engineering branches, for new discoveries and theories make radical changes from year to year in the construction and operation of electrical machinery. The engineer whose education is based only upon practical experience cannot keep up with the progress and change resulting from it, and falls behind; whereas, the man with knowledge of the theory and a mind trained by the theoretical studies and scientific reasoning, easily grasps the theory of the change and readjusts his mind to the new without difficulty or delay. Many instances may be cited of men who have been prominent as electrical engineers, who have been dropped out of place in the course of the rapid progress which has been made, on account of a lack of theoretical foundation in their knowledge. Those who have retained their positions throughout the growth of the art have done so by persistent study along theoretical lines.

In its present state electrical engineering is the most scientific of all engineering professions. A man must be to a great extent a physicist, a chemist and a mathematician, as well as be familiar with machinery and its design, in order to be a worker in the broadest field. Many of the problems connected with other branches of engineering can be solved by common sense and by one's sense of proportion as guided by experience and by the eye. But most of the problems in electricity are invisible, so to speak, and can be understood only through their expression in the form of symbols.

Probably no one will dispute to-day that the preliminary education of an electrical engineer demands a special training in those theoretical branches, mathematics, physics, chemistry and mechanics, sufficient to train his mind into accurate methods of thought and reasoning, and to supply him with the actual technical information which he will need in the practice of his profession. But theory alone is not all. The human mind is such that it works with difficulty in pure theory without a series of mental pictures to fix and coördinate the ideas, and the study of theory is likely to make little lasting impression unless the physical meaning of the theory is brought out by constant association with actual apparatus which demonstrates the application of the physical law.

The best course of training for an electrical engineer would seem to be a broad course of education in general subjects at the preparatory school before entering college, with practical work, if possible, along lines of simple mechanics, such as carpentry, in order to train the mind into a sense of proportion and the relations of parts, which is the basis of all engineering.

Next a college course with general subjects the first year; and afterward, for the remaining years of the course, those general and theoretical subjects which have a direct bearing upon the practice of the electrical profession, such as mathematics, mechanics, physics, chemistry, theoretical electricity and magnetism and thermodynamics. This should be supplemented by actual daily practical work with machinery operating by the principles covered by the theory studied, and demonstrating all the phenomena incident to the theory.

After graduation an apprentice course should be pursued in some large electrical manufacturing establishment where the commercial relations of the knowledge acquired in college can be clearly set forth. Large machines may be operated which are not available at a college and experience in the installation of large plants may be obtained, and experience gained in the designing departments where all kinds of commercial apparatus are laid out.

After a few years of this training, specialization may begin along the lines selected for the life work, but preferably not before. A man makes a mistake to consider himself a qualified electrical engineer after he has been graduated from college, for he is not one. His mind has been trained into a condition where he can readily absorb the principles of the electrical profession, but that is all, and the subsequent apprentice training is as important as the college course, in order to acquire the broad viewpoint from which to make the correct start in the direction in which a man is best fitted. It perhaps means a smaller income the year after graduation from college, but it means much more at the end of five years.

But theory and practice are not the only elements necessary for the successful engineer. There are many qualities required in common with other professions; executive ability, business knowledge, presence of mind and ability to handle men, nerve and resourcefulness in handling machinery in times of emergency, are all necessary for the successful engineer. These elements can not be acquired in the study of theory and practice alone, and

many men who have stood high in their college courses have afterward failed in the practice of their profession because of a lack of these qualities.

The study of chemistry becomes more and more important as the profession advances, for the branch of electro-chemistry is rapidly developing and is likely to become one of the largest fields in the application of electrical science.

And almost above all comes a training in the English language. No man who cannot express himself clearly and concisely in writing or in conversation can hope to attain a prominent position in his profession.

The education of an electrical engineer, however, must never be considered as complete. The art advances so rapidly that constant study is necessary, even to keep up with the progress of the times. But an electrical engineer should be willing to do more than this. He should study to keep ahead of progress and do his share toward the instruction of others.

A paper presented at the 19th Annual Convention of the American Institute of Electrical Engineers, Great Barrington, Mass., June 21th, 1902

A PROPOSED REFORM IN TECHNICAL TRAINING

BY EDWARD B. RAYMOND.

Those who are called upon to select a man for certain duties, although able to form in their own minds an opinion as to the qualifications necessary, frequently experience difficulty in finding such a person as they require. Most men do not appear to realize that intelligent and conscientious work is the basis of advancement, and that industry guided by intellect is invincible. Although this statement may not be generally appreciated, it is the result of many years of experience in the selection of employes, and applies to college graduates as well as others. This condition of affairs is largely due to early training. Young men who have been reared without due consideration of the economy and self-denial which has enabled their parents to support them while they were being educated, do not take their life work with the necessary earnestness, and are apt to drift along without thought as to whether or not their efforts are tending in the proper direction.

As under existing social conditions there can be no scientific selection of parents, we are necessarily compelled to deal with the problem as it confronts us, so that it is by no means a simple matter to determine the most suitable future employment for a boy who has not yet developed any leaning toward a distinctive line of work.

When a boy enters the High School, either parents or teacher should decide upon the line of his life work. It is too early for him to judge of his own natural ability, and it is the experience of the writer that most college graduates fail in determining

their proper sphere of action, and this is usually apparent to themselves. It is so seldom that positive tendencies appear in a boy, that his natural ability should be carefully studied, and a decision reached as to his future course.

Some of the great masters of the violin will not undertake to teach a pupil who has passed his eighth year, as they hold that the initial training should begin at that age. The writer believes that a similar rule should apply to engineers, and that this work should be started in the High School.

Supposing that electrical engineering has been chosen. What qualifications are essential to success? The student should possess health, character, courage and intellect. He should be thoroughly impressed with the understanding that work, hard work, constant work, is the absolutely essential foundation for future success.

These conditions refer more especially to young men of average ability. The exceptions, who are generally recognized as men of genius, are exotics, and the ordinary rules of advancement do not apply to them. They soar above their colleagues by reason of their superior fitness, and we admire and honor them for their recognized ability, without attempting to analyze the causes, for we know that to be impossible.

Every man has the ability to do certain things with the best possible results. One of these things is work. But in addition to this we should have trained minds, and accumulate knowledge of detail.

There exists in the electrical profession above all others, a demand for the lowest grade of work as well as the highest. The engineer should be thoroughly trained in the various lines of practical work, in order to instruct or guide others. He must possess the necessary data, and his mind must be trained to utilize it, in order to make the proper calculations, and predetermine results. While all this is true in any branch of engineering, it is especially so in the electrical, as we cannot rely simply upon judgment and intuition. Something more is required to enable an engineer to design and calculate properly the required output of an induction motor, or determine the phases of cross-currents between alternators, whose prime movers are pulsating in frequency, or hundreds of other cases arising in practice.

To sum up, therefore, we need broad-minded men with intellect, strength, training and purpose. How can we best obtain them? We naturally turn to the college—but how much is asked of it?

Men have entered without knowledge of the line of work they are to adopt; often deficiently trained. Their view of life is a fraction with ease and comfort cubed as the numerator, with work to the one-third power in the denominator. To make successful men, this fraction must be reversed. If not done in college, it will be done through stress of the duties which the graduate assumes upon beginning his life work. If this training comes too late, another man already seasoned will forge ahead, for the handicap is too serious for a term of active life, none too long at the best.

Our professors, then, should be men of force of character as well as of intellectual attainment, and the courses at college should be so arranged that recitation rooms and laboratories may be regarded by the students as we look upon our offices.

At this stage of the young man's education, it is the writer's idea that details should be put into second place, as at that time of life they are likely to be only superficial.

The technical college should attract by its atmosphere only men with a purpose, and so the training must be correctly prepared. Some of our colleges make a poor showing in this respect, possibly from improper organization, failure to reach the individual, or inability to inspire the working spirit. It is the writer's opinion that the colleges should return to the district school principle by stopping elective courses, contracting the list of studies and by encouraging the students to specialize. Then, if the professor is able to get hold of each student personally and instill into his mind the necessity for hard work, a long step will have been taken toward the perfect engineering course. The young man graduated from such an institution will go out into the world with a real equipment for successful work in his particular sphere of usefulness.

One of the most essential qualifications of the successful engineer is that he shall be filled with a desire for continual study. Then is the time for him to get his knowledge of real detail, amplifying the general knowledge obtained in college by practical investigation. In short, the college graduate should consider that the knowledge gained at the university is only a start and not a suggestion of a finish.

The writer is a strong advocate of the strictly technical course in the training of electrical engineers. The technical college should drop from its curriculum studies which are likely to be taken up after graduation. The writer believes that such a

college will turn out men better qualified for professional work, for when properly trained the graduated engineer will devote a portion of each week to study, and will do this from a natural inclination to study. Details of all subjects that he lacks will be obtained without great effort. As he accumulates money, he will naturally turn to political economy and business law; reading will turn him to history, and daily writing will lead him to use good grammar and expression.

The chances of success in the case of a man thoroughly grounded in technical information are vastly better than those of the man who has gained general information at the expense of technical training. This point is well illustrated by the wonderful success of many of the most noted men in our profession without college training. They had the essential characteristics for success, mind, application and a desire to study, and their success has been the result of those qualifications.

The ideal college, then, would be that which teaches simplicity, concentration, hard work; which discourages all that is superficial; which weeds out the studies that are not essential to the particular course being pursued, and devotes all the more attention to those that are essential.

For the boy in the High School who intends to be an electrical engineer, it may be suggested that for about six weeks of his last two summer vacations at the High School, he should work in the machine shop of some manufacturing electrical concern. This will give him very valuable initial experience. During his college course the student in electrical engineering should spend a part of each summer in similar practical work, supplementing it, perhaps, with work in a foundry or pattern shop. The draughting-room at college would mean much more to such a man than to the ordinary student.

The writer would suggest, therefore, in line with these ideas, that from college electrical courses such studies as French and German, rhetoric and English composition, history, English literature and political economy, be dropped. One college, to the writer's knowledge, has, besides all these studies, dropped bridge construction, surveying and highway building. In place of the studies discarded, more stress could be laid upon mathematics, physics, mechanics, chemistry, thermodynamics and the laws of electricity. There should be enough of these studies to give, in addition to mind training, excellent detail knowledge of the subjects studied.

A feature of the college that may be made especially interesting and instructive is the arrangement of frequent lectures, or talks, by men eminent in their profession. Such men are always willing to give to others the benefit of their own great experience; and their talks must be inspiring to the student, even if the lecture is not understood in detail. Such talks are instructive for the professor as well as the undergraduate, giving excellent inspiration by illustrating what has actually been accomplished.

In conclusion let me say that I do not wish to give the impression that the college is a failure. It is doing wonderful work, and deserves great credit; but in electrical engineering education as well as in everything else, there is nothing that cannot be improved.

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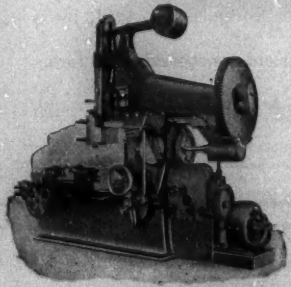

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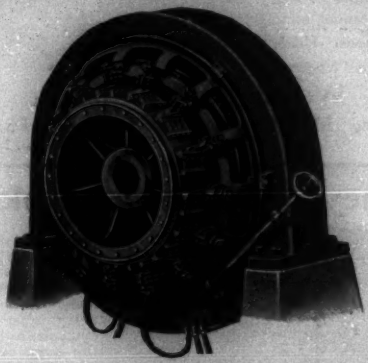

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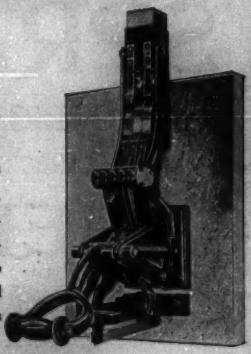

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Roney Mechanical Stokers

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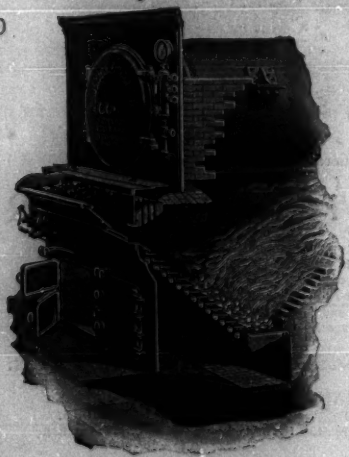

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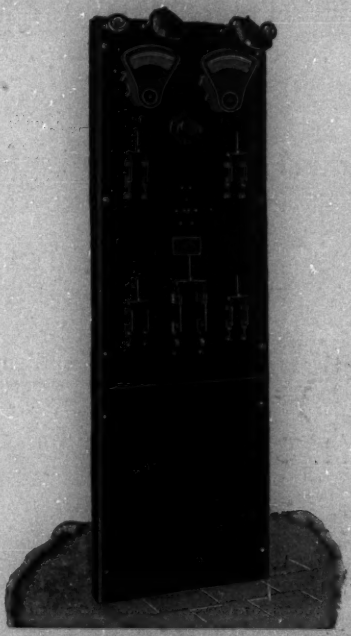

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